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BOUNDARY LAYER STUDIES ON A SPINNING  
TANGENT - OGIVE - CYLINDER MODEL

Walter B. Sturek

July 1975

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20. ABSTRACT (Continued):

normal forces were measured using the strain-gage balance technique for different boundary layer configurations. These measurements revealed a substantial sensitivity of Magnus force to the boundary layer configuration. A preliminary comparison of the Magnus measurements to the theory of Vaughn and Reis yielded poor agreement. The data have been tabulated to facilitate their use in the evaluation of proposed theoretical models of the Magnus effect.



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## I. INTRODUCTION

Emphasis has recently been placed on obtaining increased range and greater payload capacity for new Army projectile shapes. These requirements have led to projectile shapes with long slender ogives, increased length and boattailed afterbodies. The new designs have resulted in decreased drag; however, the stability of these projectiles has also been decreased. Thus, these new shapes are more susceptible to a Magnus induced instability. Also, the increased length of these new shapes has contributed to an increase in the Magnus moment. These factors have resulted in renewed interest in the study of the Magnus effect.

This report describes an experimental study of the effects of spin on boundary-layer development over a seven caliber tangent-ogive-cylinder model in supersonic flow. This experimental study is part of the BRL Magnus research effort which is being undertaken to develop a better understanding of the physics of the Magnus effect. The objectives of this particular experiment are to: (1) examine the effect of spin on boundary-layer development; (2) examine the significance of the boundary-layer configuration (laminar, transitional or turbulent) on the resulting Magnus force experienced by the model; and (3) provide detailed experimental data which will be of value in evaluating theoretical models of the Magnus effect. This report is supplementary to Reference 1 which reports an experimental investigation of the flow over a spinning cone model.

## II. THE EXPERIMENT

The experimental study consisted of two parts: (1) an optical study of the effects of spin on boundary-layer transition; and (2) the effect of different boundary-layer configurations on the Magnus force as measured using a strain-gage balance.

### A. Test Facility

The test facility<sup>2</sup> used was Supersonic Tunnel No. 1 at the Ballistic Research Laboratories (BRL). This is a continuous flow facility with a flexible plate symmetric nozzle. The test section has a height of 38 cm

1. W. B. Sturek, "Boundary Layer Studies on a Spinning Cone," BRL Report No. 1649, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, May 1973. AD 762564.
2. J. C. McMullen, "Wind Tunnel Testing Facilities at the Ballistic Research Laboratories," BRL Memorandum Report No. 1292, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, July 1960. AD 244180.

and a width of 33 cm. The nominal tunnel operating conditions for each test are given in Table I. The total temperature was controlled within  $\pm 1^\circ\text{K}$  and the total pressure was maintained within  $\pm 0.4$  percent during each individual test run.

#### B. Model

The model used for these tests was a seven caliber long tangent-ogive-cylinder with a one-caliber ogive section. The diameter of the cylinder portion was 5.08 cm. A view of the model mounted in the test section is shown in Figure 1. The model was suspended on ball bearings and an internal air driven turbine was used to drive the model in spin. The model was made of high strength aluminum alloy and was highly polished. The model was dynamically balanced to a tolerance of 2.1 gm-cm.

#### C. Optical Study

Spark shadowgraphs were taken of the flow over the model while mounted on an offset strut. Two offset struts were used giving angles of attack of  $2^\circ$  and  $4^\circ$ . A picture of these offset struts is shown in Figure 2. Using the roll head, pictures were taken at  $15^\circ$  increments in azimuth for azimuthal angles from 0 to  $+180^\circ$  and from 0 to  $-90^\circ$ . Spark shadowgraphs were obtained for  $M = 2, 3$ , and 4 and for spin rates of 0, 8,000, 16,000, and 24,000 rpm. The tunnel total pressure was maintained at a high value in order to enhance the occurrence of natural transition to turbulence before reaching the base of the model on the windside. The spark shadowgraphs were taken while holding the model at a constant spin rate. A spark shadowgraph of the flow over the model is shown in Figure 3 for  $M = 2$ ,  $\alpha = -4^\circ$ , and  $\omega = 0$  rpm.

#### D. Strain-Gage Balance Measurements

Magnus and normal forces were measured using the strain gage balance technique for different boundary-layer configurations. The boundary-layer configuration refers to the relative regions of laminar and turbulent boundary layer occurring on the model for a particular flow condition. The flow conditions obtained were: (1) low tunnel total pressure--predominantly laminar boundary layer; (2) high tunnel total pressure--approximately comparable regions of laminar and turbulent boundary layer (same operating conditions as that for the optical study); and (3) high tunnel total pressure with the boundary layer tripped to turbulent by a band of #80 sand grit, 0.63 cm wide, placed 2.5 cm from the tip of the model. The effectiveness of this trip is indicated in Figure 4 which shows a spark shadowgraph of the flow for  $M = 2$ ,  $\alpha = -4^\circ$ , and  $\omega = 0$ . The boundary-layer trip performed well for the case shown here. At  $M = 4$ , the trip was somewhat less effective, but was considered satisfactory.

The strain gage balance used was SB219. This is a moment-type balance, designed and fabricated at the Exterior Ballistics Laboratory (EBL). This balance has three sets of gages: (1) forward normal, forward yaw; (2) aft normal, aft yaw; and (3) aft-aft yaw. The limiting loads are 60 in-lbs (6.78 m-N) in pitch and 43 in-lbs (4.86 m-N) in yaw at the forward position; 80 in-lbs (9.04 m-N) in pitch and 53 in-lbs (5.99 m-N) in yaw at the aft position; and 146 in-lbs (16.50 m-N) in yaw at the aft-aft position.

The Magnus measurements were made while holding the model at a fixed angle of attack. The model was spun up to 30,000 RPM using the internal air driven turbine, the turbine air was shut off, and data were recorded on magnetic tape at fixed intervals of time while the model coasted to zero spin. The spin down time was typically six minutes--very favorable for obtaining good quality Magnus data.

Normal force and moment data were obtained while the model was spinning, and also while the model was slowly moved in angle of attack from +12 to -4 degrees with zero spin.

The accuracy of the force measurements is estimated to be within  $\pm .0006$  in side force coefficient and within  $\pm .005$  in normal force coefficient.

### III. DISCUSSION OF THE RESULTS

#### A. Effect of Spin on Boundary-Layer Transition

The location of boundary-layer transition was determined from the spark shadowgraphs as the position where the boundary layer appeared to be fully turbulent. An example of this determination is indicated in Figure 3. No attempt has been made to relate this criteria for transition to other means such as wall shear stress or wall heat transfer. It should be emphasized here that no attempt to relate the transition data obtained here to atmospheric flight will be made. These data are being obtained to better understand the influence of spin on boundary-layer development as it occurs on a wind tunnel model in order that a meaningful comparison can be made between calculations of Magnus effects and wind tunnel measurements. Figure 5 shows the coordinate system used in presenting the data along with the direction and sense of the forces, moments, and angles.

The boundary-layer transition data are shown in Figures 6 through 8. The data are plotted as the distance in calibers from the base of the model to the location of boundary-layer transition. A solid line has been drawn to indicate what is felt to be the trend of the data. The cross-hatched region represents the region of turbulent boundary layer while the clear region represents laminar boundary layer.

The data indicate substantial scatter for some cases. This is especially true for the  $M = 2$  data. The cause of this excessive scatter is believed to be linked with the intermittent unsteady diffuser flow that occurred at  $M = 2$ . However, for the most part, a trend of the data as a function of azimuthal position and spin rate is apparent. The trend for the data shown in Figure 7a is particularly well defined. The trends with spin are: (1) transition is delayed where the crossflow velocity is in the same direction as the surface spin; and (2) transition occurs earlier where the crossflow velocity opposes the spin velocity.

The peculiar dip in the trend of the data for  $\phi \approx 180^\circ$  is sufficiently persistent to lead one to suspect that this observation is not experimental uncertainty. In considering the physics of this three-dimensional boundary layer flow, it is apparent that  $\phi = 180^\circ$  is a rear stagnation point in the crossflow plane. Although the inviscid azimuthal velocity is zero at this position, the azimuthal velocity derivative is not zero and the flow is turned as it approaches this crossflow stagnation point. The unusual behavior of the transition location at the  $\phi \approx 180^\circ$  position is likely a manifestation of this flow situation.

#### B. Magnus Force Measurements

A comparison of Magnus force measurements is shown in Figure 9 for the  $M = 3$  data. These data are plotted as side force coefficient versus non-dimensional spin rate for the three different boundary-layer configurations. The significant trends of the data are: (1) the low  $p_o$  ( $Re_D = 0.59 \times 10^6$ ) data--predominantly laminar boundary layer--are nonlinear with spin rate and greater in magnitude than the high  $p_o$  ( $Re_D = 1.06 \times 10^6$ ) data with natural boundary-layer transition; (2) the high  $p_o$  data, with and without the boundary-layer trip, are linear with spin rate; and (3) the tripped turbulent boundary layer data are greater in magnitude at all spin rates than either case with natural boundary layer transition.

Additional examples of the Magnus force measurements are shown in Figures 10 and 11 for  $M = 2$  and 4. These data exhibit trends similar to that described above. A complete tabulation of the force measurements and boundary layer transition data is given in Table II.

The only theory presently available for predicting Magnus effects on bodies of revolution in supersonic flow is that published by Vaughn and Reis<sup>3</sup>. This theory is a semi-empirical approach and attempts to

3. H. R. Vaughn and G. E. Reis, "A Magnus Theory for Bodies of Revolution," SC-RR-72 0537, Sandia Laboratories, Albuquerque, New Mexico, January 1973; also, AIAA Journal, Vol. 11, No. 10, p. 1396, October 1973.

include the effects of vortex formation, centrifugal pressure distribution and boundary-layer transition on the Magnus force experienced by the spinning projectile in addition to the conventional contribution of asymmetric boundary-layer development. The theory is presented as closed form solutions for Magnus force and moment for several body configurations. The closed form solutions for an ogive-cylinder body have been taken directly from Reference 3 and the data of this experiment used as input to calculate Magnus force and moment.

Two examples are shown in Figures 12a and 12b comparing the calculated and experimental Magnus force for two different boundary-layer configurations. The data are plotted as Magnus force coefficient versus spin rate. In Figure 12a--high  $p_o$  with natural transition--the theory is approximately 60% greater in absolute value than the experiment. The theory indicates nonlinearity with spin similar to that indicated in the experimental data. In Figure 12b--high  $p_o$  with tripped boundary layer--the theory is greater in absolute value than the experiment by almost 200%. Thus, it is seen that Vaughn's theory overpredicts the Magnus force and is overly sensitive to boundary-layer configuration, at least for the results considered here. These results are typical of comparisons made utilizing all the data tabulated in Table II.

#### C. Normal Force Measurements

Examples of the normal force measurements are shown in Figures 13a-c. The data are plotted as normal force coefficient versus angle of attack, and were obtained as the model was slowly pitched in angle of attack from  $+12^\circ$  to  $-4^\circ$  while the model was not spinning. These data are linear for  $\alpha \leq 4^\circ$ . For  $\alpha > 4^\circ$ , the data become increasingly nonlinear indicating the increasing influence of vortex formation on the surface pressure distribution. These data also indicate that the normal force coefficient is relatively insensitive to Reynolds number and boundary-layer configuration.

### IV. CONCLUDING REMARKS

An experimental investigation of the effects of surface spin on boundary-layer development and Magnus force for a seven caliber tangent-ogive-cylinder model with a one-caliber ogive at  $M = 2, 3$ , and 4 has been reported.

The data indicate that boundary-layer transition is affected by spin in a manner consistent with the physical picture of the flow. It has also been shown that Magnus force is significantly influenced by the boundary-layer configuration. These data strengthen the need for a good theoretical model of the effects of surface spin on boundary-layer development in order for Magnus effects to be calculated with sufficient confidence to be useful in projectile design.

The data from this experiment have been tabulated to facilitate their usefulness in evaluating theoretical models of Magnus. A preliminary comparison of these data with Vaughn's theory indicated that the theory overpredicted the Magnus force and was overly sensitive to the boundary-layer configuration.

Table I. Wind Tunnel Nominal Operating Conditions

<u>M</u>	<u><math>p_o, N/M^2 \times 10^{-6}</math></u>	<u><math>T_o, ^\circ K</math></u>	<u>Test Type</u>	<u>Config.</u>	<u><math>Re_D \times 10^{-6}</math></u>
2	.214	310	Optical	10	1.26
2	.107	310	Force	10	0.63
2	.214	310	Force	10	1.26
2	.214	310	Force	20	1.26
3	.300	310	Optical	10	1.06
3	.167	310	Force	10	0.59
3	.300	310	Force	10	1.06
3	.300	310	Force	20	1.06
4	.504	310	Optical	10	1.06
4	.372	310	Force	10	0.79
4	.504	310	Force	10	1.06
4	.504	310	Force	20	1.06

NOTE: Configuration (CONFIG.) = 10, basic model without boundary layer trip

= 20, basic model with boundary layer trip consisting of a .63 cm wide band of #80 sand grit placed 2.5 cm from the model leading edge

TABLE II. TABULATED FORCE AND BOUNDARY LAYER TRANSITION DATA

RUN	M	ALPHA	PO	TO	A	CY	H	C	CYM	D	REL	BOUNDARY-LAYER	LEE	WIND	CN	CM	MCP
121.0	2.0	1.20	.214	310.0	-.009161		.000000	-.023890		.000000	8.8577		.261	.757	.0619	.3541	5.72
122.0	2.0	2.42	.214	311.0	-.024480		.000000	-.033410		.000000	8.8319		.298	.803	.1234	.7106	5.76
123.0	2.0	4.82	.214	312.0	-.058940		.028050	-.059790		.022520	8.7538		.273	.931	.2555	1.4475	5.67
124.0	2.0	7.21	.214	311.0	-.110300		.025070	-.097700		-.007631	8.7825		.249	1.000	.4121	2.2547	5.47
126.0	2.0	-1.20	.214	310.0	-.009328		.000000	.035870		.000000	8.8395		.261	.603	-.0581	-.3465	5.96
127.0	2.0	-2.43	.213	310.0	.026360		.023280	.021530		.134200	8.8411		.273	.507	-.1207	-.7081	5.87
128.0	2.0	-4.83	.214	310.0	.055280		.000000	.073040		.000000	8.8402		.347	.537	-.2496	-1.4396	5.77
132.0	2.0	1.09	.107	310.0	-.029890		.033550	.001320		-.057930	4.4215		.715	.926	.0574	.3392	5.91
133.0	2.0	2.20	.107	310.0	-.056140		.075700	-.030910		.010160	4.4254		.695	1.000	.1120	.6657	5.94
134.0	2.0	4.38	.107	310.0	-.082710		.077170	-.114600		.090960	4.4145		.606	1.000	.2321	1.3336	5.75
135.0	2.0	6.58	.107	310.0	-.150600		.146500	-.169700		.034050	4.4242		.571	1.000	.3691	2.0638	5.59
136.0	2.0	8.74	.107	310.0	-.214500		.067340	-.214100		-.121100	4.4134		.562	1.000	.5398	2.8758	5.33
137.0	2.0	10.88	.107	310.0	-.226800		.0219400	-.246500		-.152000	4.4071		.557	1.000	.7604	3.8106	5.01
138.0	2.0	-1.07	.107	310.0	-.037800		-.101700	-.013980		.174300	4.4094		.746	.921	-.0484	-.2859	5.90
139.0	2.0	-2.19	.107	310.0	.058940		-.120400	.026520		.087280	4.4123		.679	1.000	-.1047	-.6181	5.90
140.0	2.0	-4.38	.107	310.0	.079110		-.076730	.106700		.022090	4.4138		.616	.874	-.2202	-1.2912	5.86
142.0	3.0	1.12	.300	311.0	-.012000		.000000	-.017340		.000000	7.4376		.544	.913	.0593	.3222	5.43
143.0	3.0	2.22	.300	312.0	-.026420		.013170	-.040820		.026160	7.4264		.557	.988	.1233	.6616	5.37
144.0	3.0	4.42	.299	312.0	-.061350		.042910	-.086960		.058280	7.4222		.569	1.000	.2222	1.3592	5.18
145.0	3.0	6.61	.300	313.0	-.143400		.170800	-.124300		-.003151	7.4104		.557	1.000	.4324	2.1236	4.91
146.0	3.0	8.72	.299	313.0	-.218500		.235700	-.138400		-.196500	7.3836		.000	.000	.6431	2.9388	4.57
147.0	3.0	-1.12	.299	313.0	.012900		.000000	.023860		.000000	7.3815		.757	.569	-.0650	-.3536	5.44
148.0	3.0	-2.26	.299	313.0	.025220		.000000	.042160		.000000	7.3699		.655	.581	-.1298	-.6984	5.38
149.0	3.0	-4.46	.299	313.0	.064130		-.039260	.088260		-.015570	7.3717		.557	.586	-.2702	-1.4032	5.19
156.0	3.0	1.07	.167	312.0	-.013730		.000000	-.033240		.000000	4.1489		.865	1.000	.0596	.3140	5.27
157.0	3.0	2.11	.167	312.0	-.035540		.035980	-.084440		.115200	4.1429		.815	1.000	.1219	.6440	5.28
158.0	3.0	4.24	.167	312.0	-.088830		.132400	-.218200		.397000	4.1303		.746	1.000	.2571	1.3260	5.16
159.0	3.0	6.34	.167	312.0	-.158800		.222400	-.305100		.335300	4.1263		.704	1.000	.4178	2.0460	4.90
160.0	3.0	8.39	.167	312.0	-.150100		-.027230	-.293800		-.058610	4.1334		.631	1.000	.6256	2.8459	4.55
161.0	3.0	-1.04	.167	312.0	.012120		.000000	.031540		.000000	4.1293		.872	.588	-.0562	-.3055	5.43
162.0	3.0	-2.11	.167	313.0	.025920		.000000	.067830		.000000	4.1267		.833	1.000	-.1173	-.6305	5.38
163.0	3.0	-4.24	.167	312.0	.086790		-.117100	.215400		-.363900	4.1315		.724	1.000	-.2510	-1.3040	5.20
166.0	4.0	1.08	.504	310.0	-.011960		.000000	-.035620		.000000	7.4693		.815	.975	.0579	.3042	5.25
167.0	4.0	2.13	.503	311.0	-.022800		.000000	-.062000		.000000	7.4238		.791	1.000	.1208	.6162	5.10
168.0	4.0	4.26	.504	311.0	-.063100		.066650	-.128800		.140300	7.4327		.616	1.000	.2571	1.2596	4.90
169.0	4.0	6.37	.504	311.0	-.107400		.121900	-.170400		.091560	7.4278		.603	1.000	.4174	1.9425	4.65
170.0	4.0	-1.06	.504	311.0	.010110		.000000	.027010		.000000	7.4280		.699	1.000	-.0623	-.3151	5.06
171.0	4.0	-2.12	.504	311.0	.021410		.000000	.053450		.000000	7.4228		.741	1.000	-.1250	-.6278	5.02
172.0	4.0	-4.25	.505	311.0	.060830		-.049910	.123100		-.144100	7.4210		.678	1.000	-.2604	-1.2682	4.87
179.0	4.0	1.02	.373	308.0	-.010360		.000000	-.043100		.000000	5.5610		.853	1.000	.0435	.2169	4.99
180.0	4.0	2.08	.372	309.0	-.031730		.042250	-.098400		.127900	5.5293		.853	1.000	.1071	.5311	4.96
181.0	4.0	4.17	.372	309.0	-.069770		.083110	-.159400		.132500	5.5453		.776	1.000	.2396	1.1568	4.83
182.0	4.0	6.24	.372	309.0	-.118900		.145700	-.234600		.202000	5.5505		.660	1.000	.2974	1.8259	4.59
183.0	4.0	-1.05	.372	309.0	.011400		.000000	.044900		.000000	5.5252		.850	1.000	-.0751	-.3753	5.00
184.0	4.0	-4.20	.372	309.0	.071110		-.079040	.161400		-.142300	5.5408		.840	1.000	-.2693	-1.3057	4.85

RUN	M	ALPHA	PO	TC	A	CY	S	C	CYM	D	KEL	LEF	WINT	CN	CV	ICP
193.0	4.0	1.06	.505	310.0	-.012830	.000000	.000000	-.021630	.000000	.000000	7.0010	.000	.000	.0552	.2870	5.21
195.0	4.0	4.26	.505	310.0	-.061480	.000000	.000000	-.088310	.000000	.000000	7.4627	.000	.000	.2496	1.2248	4.91
196.0	4.0	6.36	.504	311.0	-.106960	.000000	.000000	-.141800	.000000	.000000	7.4275	.000	.000	.4091	1.8950	4.64
197.0	4.0	-1.06	.504	311.0	.012800	.000000	.000000	.020590	.000000	.000000	7.4182	.000	.000	-.0606	-.3038	5.01
198.0	4.0	-2.14	.502	311.0	.026940	.000000	.000000	.044090	.000000	.000000	7.3925	.000	.000	-.1214	-.6117	5.51
199.0	4.0	-4.24	.504	311.0	.060690	.000000	.000000	.089070	.000000	.000000	7.4153	.000	.000	-.2522	-1.2291	4.87
203.0	3.0	1.09	.300	313.0	-.015850	.000000	.000000	-.020550	.000000	.000000	7.3976	.000	.000	.0561	.3028	5.40
204.0	3.0	2.20	.300	314.0	-.032890	.000000	.000000	-.042150	.000000	.000000	7.3873	.000	.000	.1200	.6292	5.33
205.0	3.0	4.42	.300	314.0	-.078090	.000000	.000000	-.094450	.000000	.000000	7.3835	.000	.000	.2586	1.3290	5.14
209.0	3.0	6.59	.299	310.0	-.136700	.000000	.000000	-.155500	.000000	.000000	7.5461	.000	.000	.4253	2.0711	4.86
210.0	3.0	-1.11	.300	312.0	.014960	.000000	.000000	.030060	.000000	.000000	7.4448	.000	.000	-.0640	-.3414	5.33
211.0	3.0	-2.23	.299	313.0	.032380	.000000	.000000	.055950	.000000	.000000	7.4093	.000	.000	-.1267	-.6735	5.31
212.0	3.0	-4.45	.300	313.0	.077870	.000000	.000000	.109000	.000000	.000000	7.3895	.000	.000	-.2641	-1.3542	5.15
215.0	2.0	1.18	.214	313.0	-.015830	.000000	.000000	-.024000	.000000	.000000	8.7373	.000	.000	.0596	.3394	5.70
216.0	2.0	2.39	.214	313.0	-.035190	.000000	.000000	-.043060	.000000	.000000	8.7395	.000	.000	.1193	.6891	5.75
217.0	2.0	4.80	.214	313.0	-.086250	.000000	.000000	-.095040	.000000	.000000	8.7242	.000	.000	.2516	1.4207	5.61
218.0	2.0	7.17	.214	313.0	-.155600	.000000	.000000	-.169600	.000000	.000000	8.7265	.000	.000	.4087	2.2108	5.41
219.0	2.0	-1.21	.214	313.0	.013660	.000000	.000000	.037990	.000000	.000000	8.7391	.000	.000	-.0577	-.3484	6.03
220.0	2.0	-2.43	.214	313.0	.033840	.000000	.000000	.059500	.000000	.000000	8.7139	.000	.000	-.1185	-.7004	5.91
221.0	2.0	-4.82	.214	313.0	.086530	.000000	.000000	.117900	.000000	.000000	8.7139	.000	.000	-.2487	-1.4315	5.76

BOUNDARY-LAYER

EXPLANATION-  
M=MACH NUMBER  
ALPHA=ANGLE OF ATTACK, DEGREES  
PO=TUNNEL TOTAL PRESSURE, PASCALS\*10E-6  
TC=TUNNEL TOTAL TEMPERATURE, DEGREES KELVIN  
CY=SIDE FORCE COEFFICIENT,  $CY = A(PD/VI) + B(PD/VI)**2$   
CYN=SIDE FORCE COEFFICIENT,  $CYN = C(PD/VI) + D(PD/VI)**2$   
REL=REYNOLDS NUMBER BASED ON MODEL LENGTH\*10E-6  
BOUNDARY LAYER(LEE,WIND)=POSITION OF BOUNDARY LAYER TRANSITION AS  
DISTANCE FROM MODEL LEADING EDGE DIVIDED BY THE MODEL LENGTH.  
TRANSITION LOCATION DETERMINED FROM SPARK SHADOWGRAPHS OF FLOW  
OVER UNSPINNING MODEL. EQUALS ZERO FOR TRIPPED BOUNDARY LAYER,  
EQUALS 1.0 FOR BOUNDARY LAYER REMAINING LAMINAR TO BASE OF MODEL.  
CN=NORMAL FORCE COEFFICIENT  
CM=PITCHING MOMENT COEFFICIENT  
NCP=LOCATION OF CENTER OF PRESSURE, NCP=CM/CN  
ALL MOMENTS ARE REFERENCED TO THE MODEL BASE

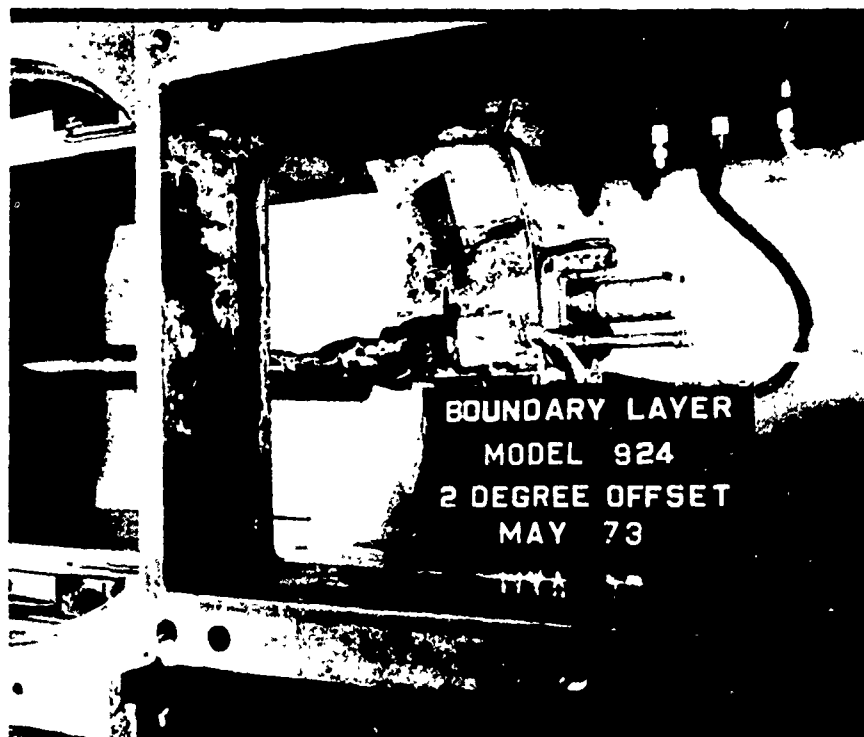
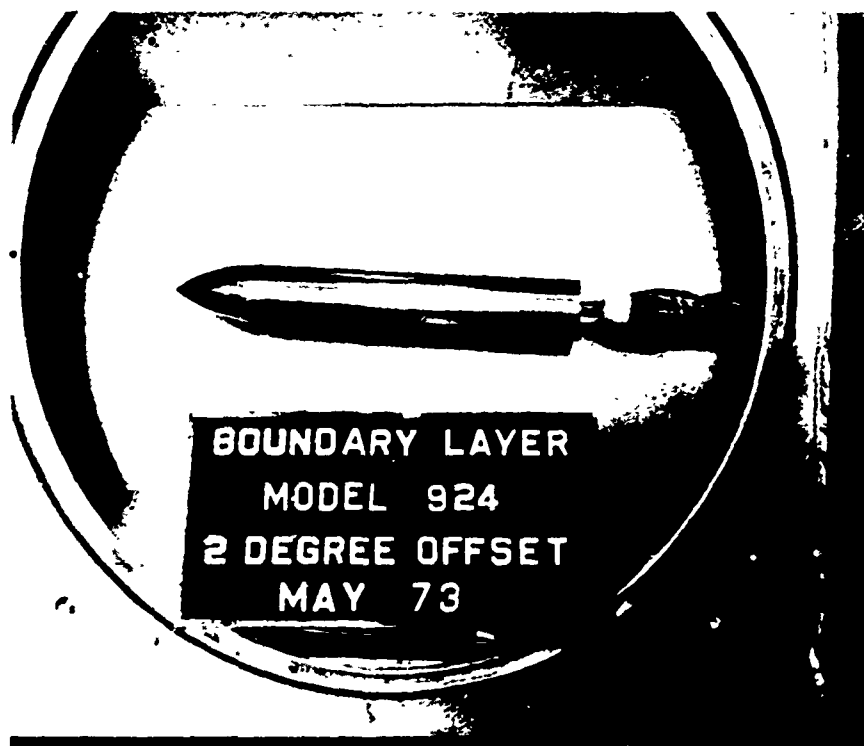


Figure 1. View of Tangent-Ogive-Cylinder Model as Mounted in the Test Section of Supersonic Wind Tunnel No. 1

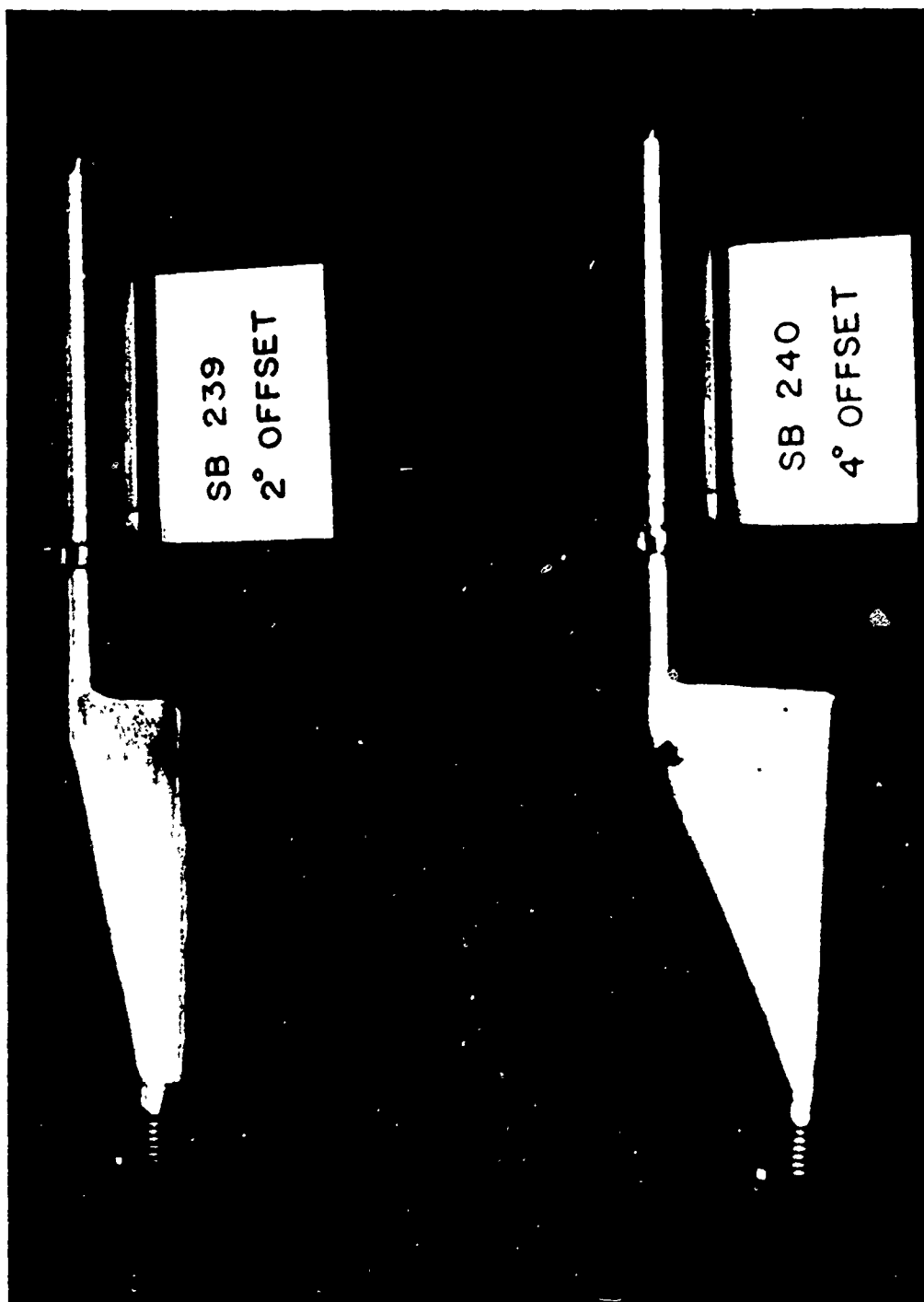


Figure 2. Offset Struts Used in the Optical Study

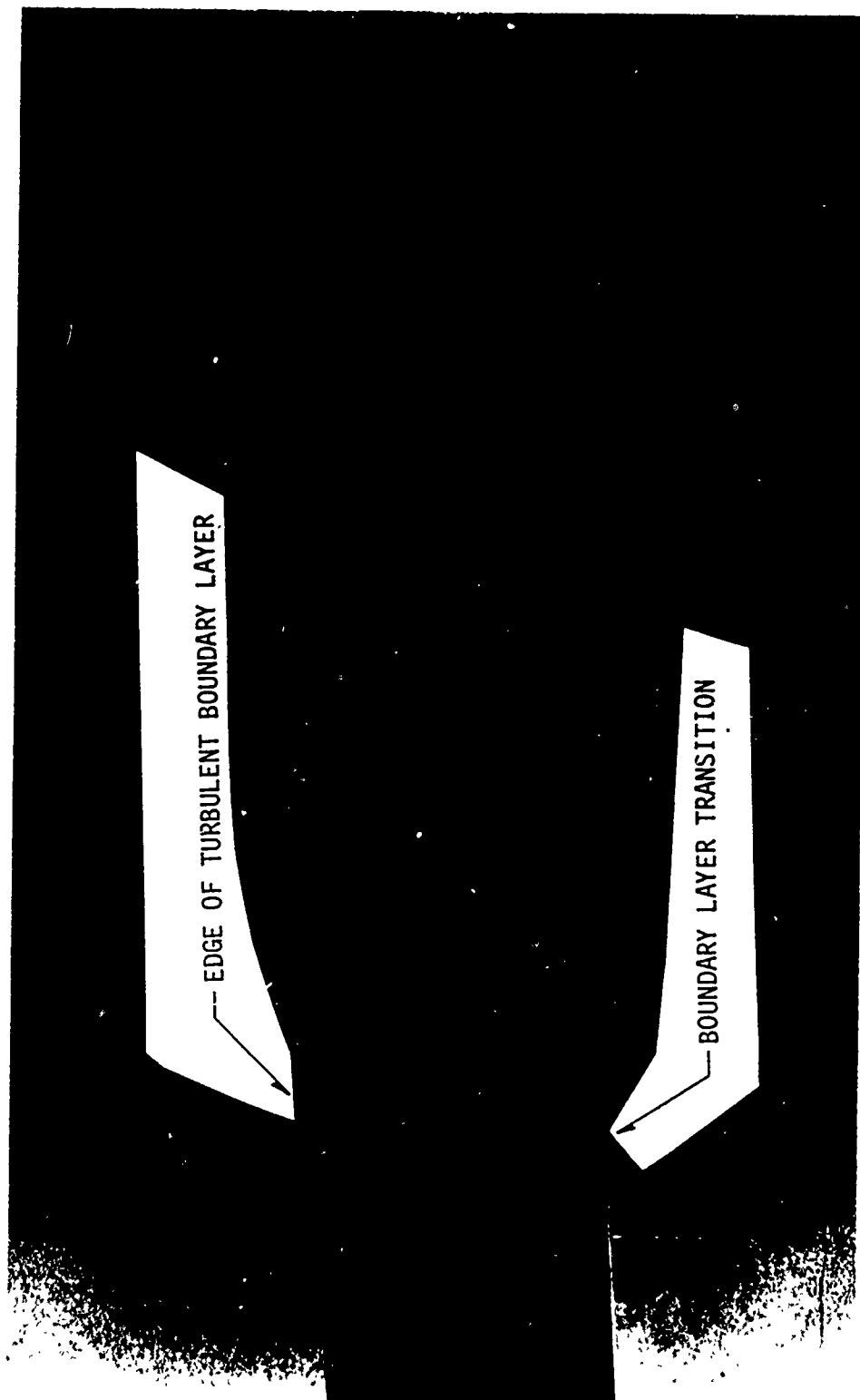


Figure 3. Spark Shadowgraph Showing Natural Boundary Layer Transition,  
 $M = 2$ ,  $\alpha = -4^\circ$ ,  $Re_x = 8.8402 \times 10^6$

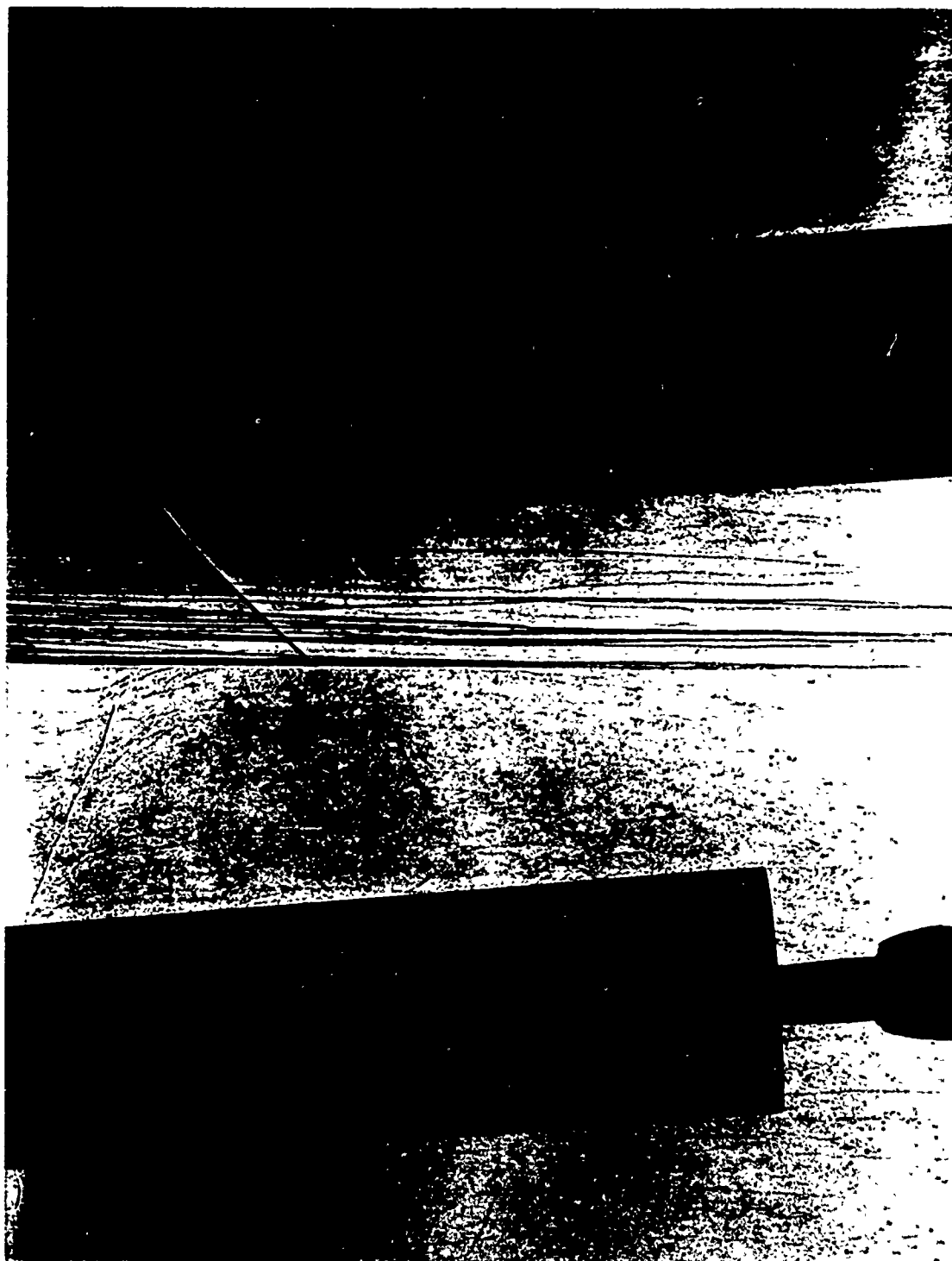


Figure 4. Spark Shadowgraph Showing Boundary Layer Tripped  
Using a Band of No. 80 Sand Grit,  $M = 2$ ,  $\alpha = -4^\circ$ ,  
 $Re_\lambda = 8.7139 \times 10^6$

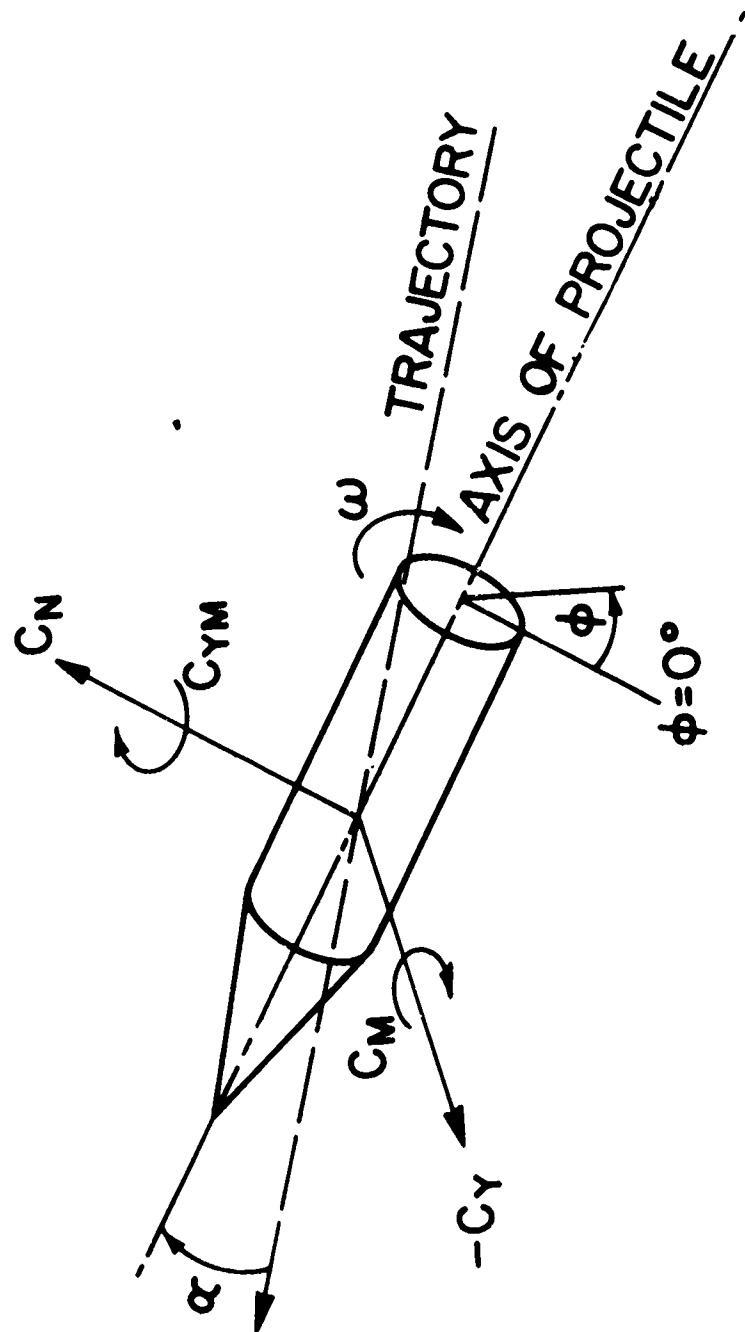


Figure 5. Coordinate System Showing the Direction and Sense of Forces, Moments and Angles

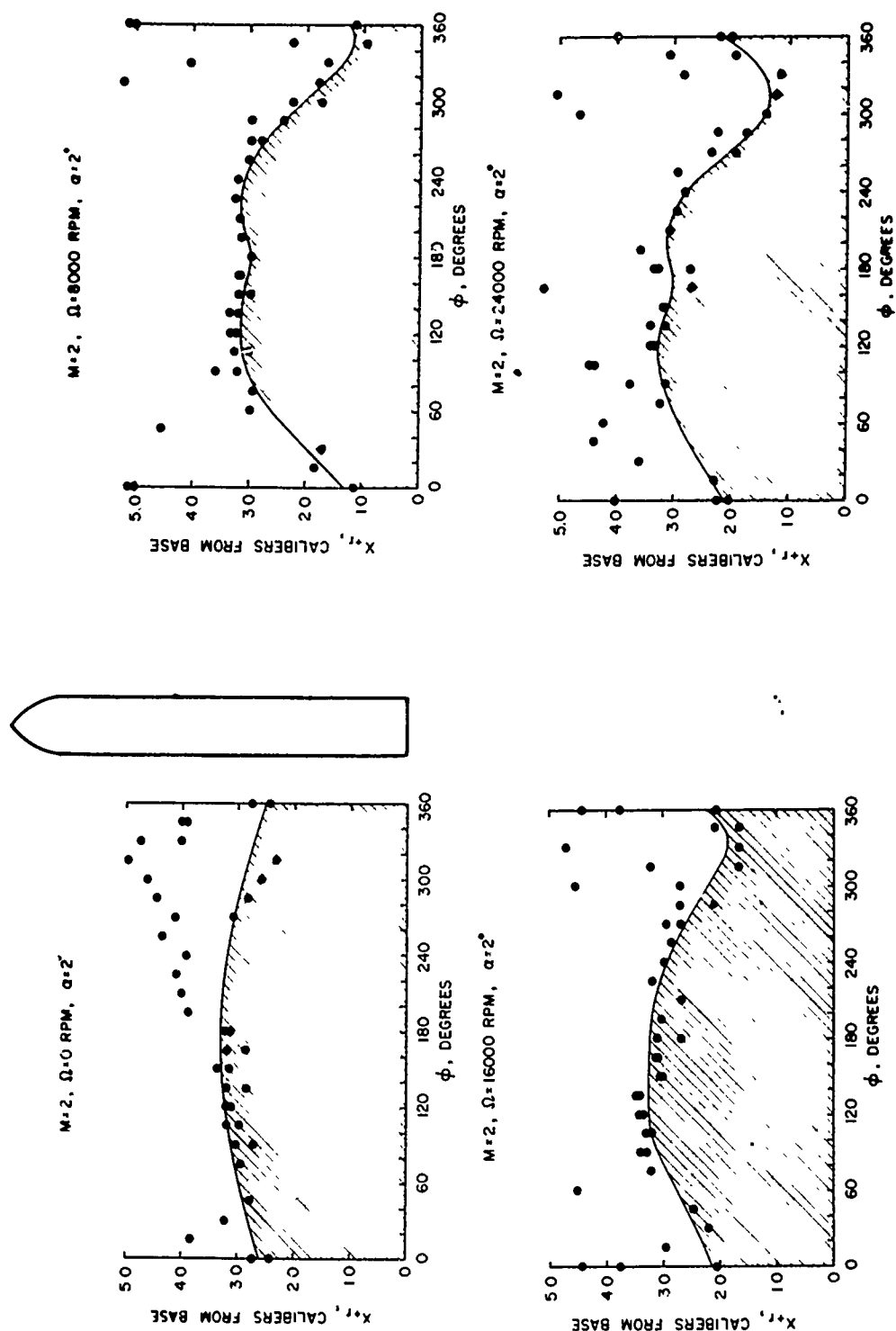


Figure 6. Boundary Layer Transition Data

a.  $M = 2, \alpha = 2^\circ$

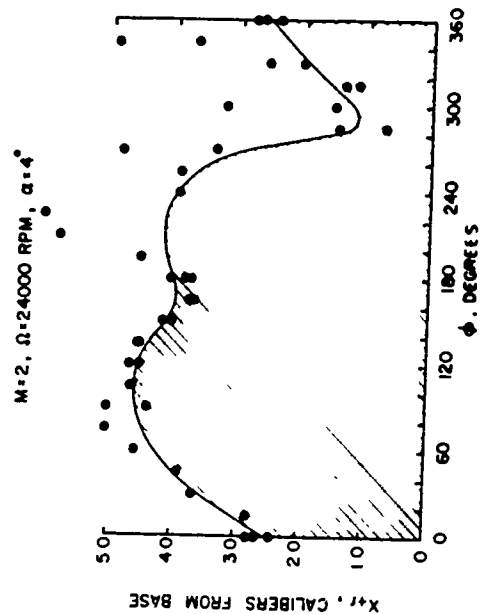
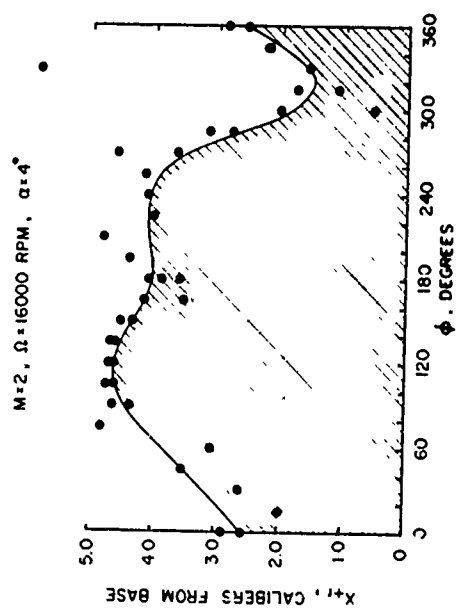
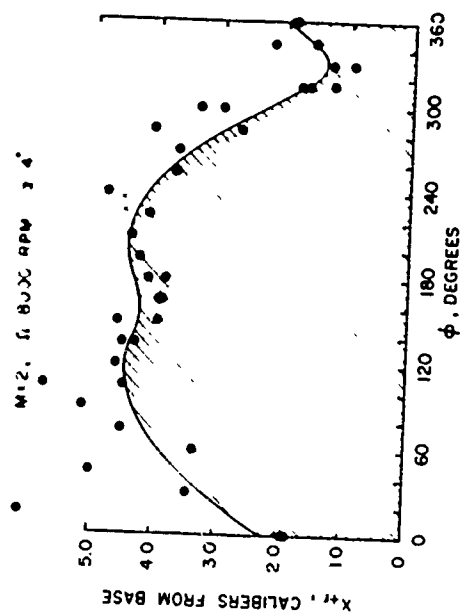
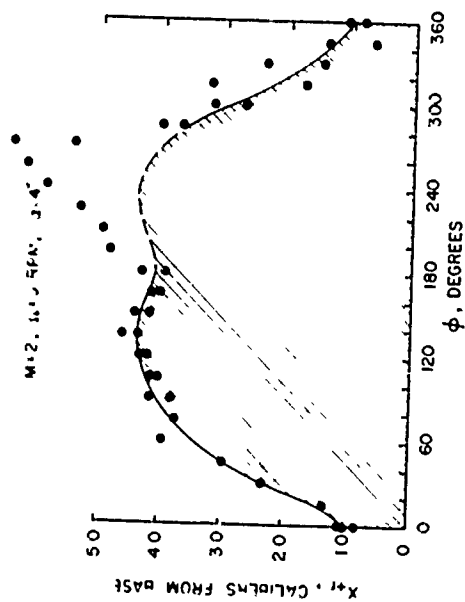
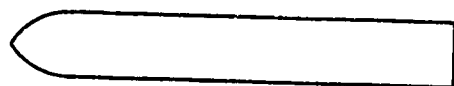


Figure 6. Concluded

b.  $M = 2, \alpha = 4^\circ$

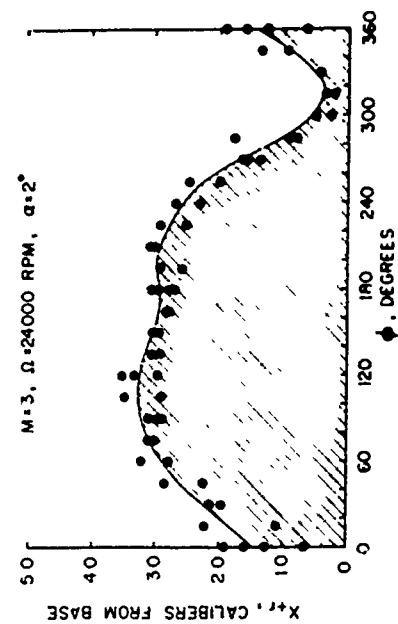
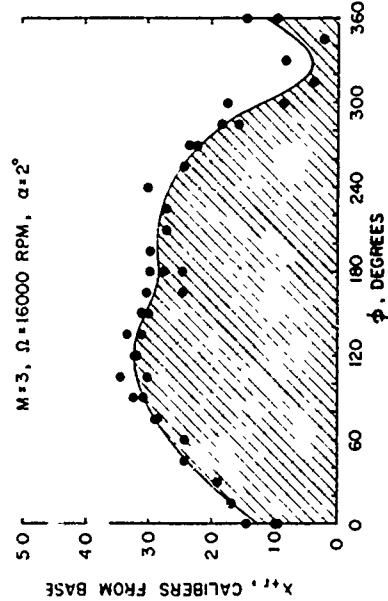
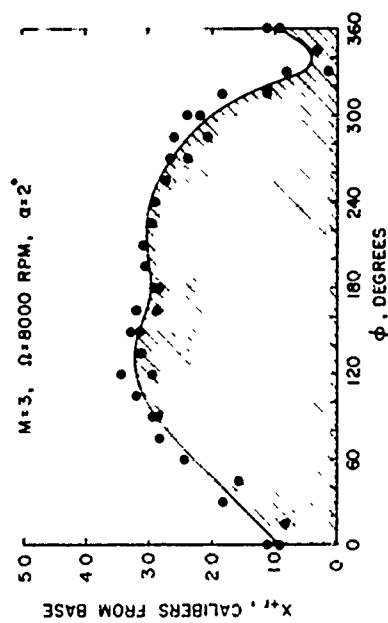
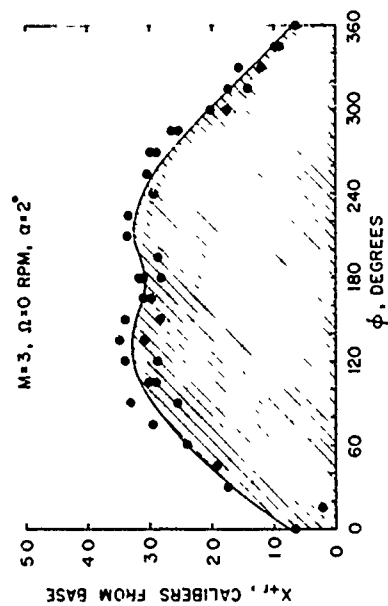
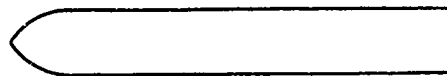
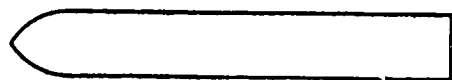
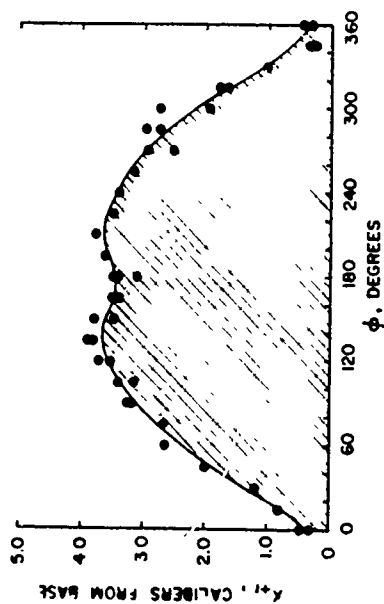


Figure 7. Boundary Layer Transition Data

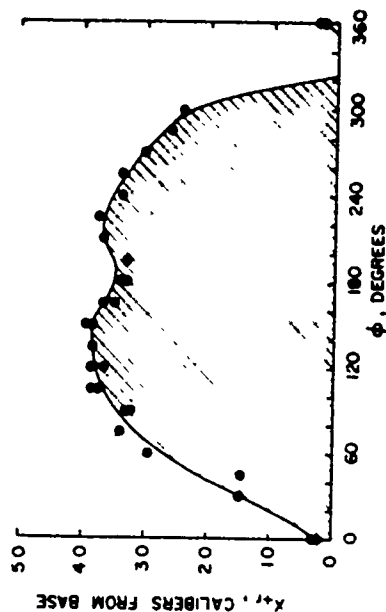
a.  $M = 3, \alpha = 2^\circ$



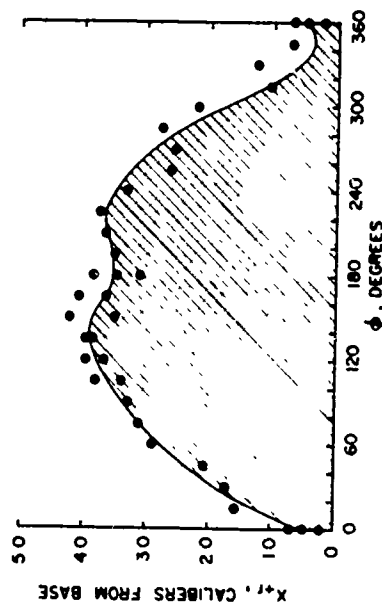
$M=3, \Omega=0 \text{ RPM}, \alpha=4^\circ$



$M=3, \Omega=8000 \text{ RPM}, \alpha=4^\circ$



$M=3, \Omega=16000 \text{ RPM}, \alpha=4^\circ$



$M=3, \Omega=24000 \text{ RPM}, \alpha=4^\circ$

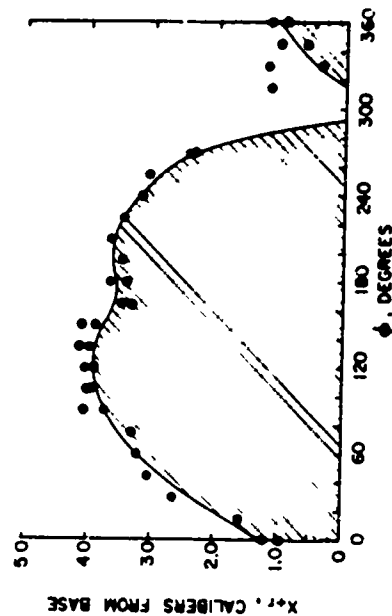


Figure 7. Concluded

b.  $M=3, \alpha=4^\circ$

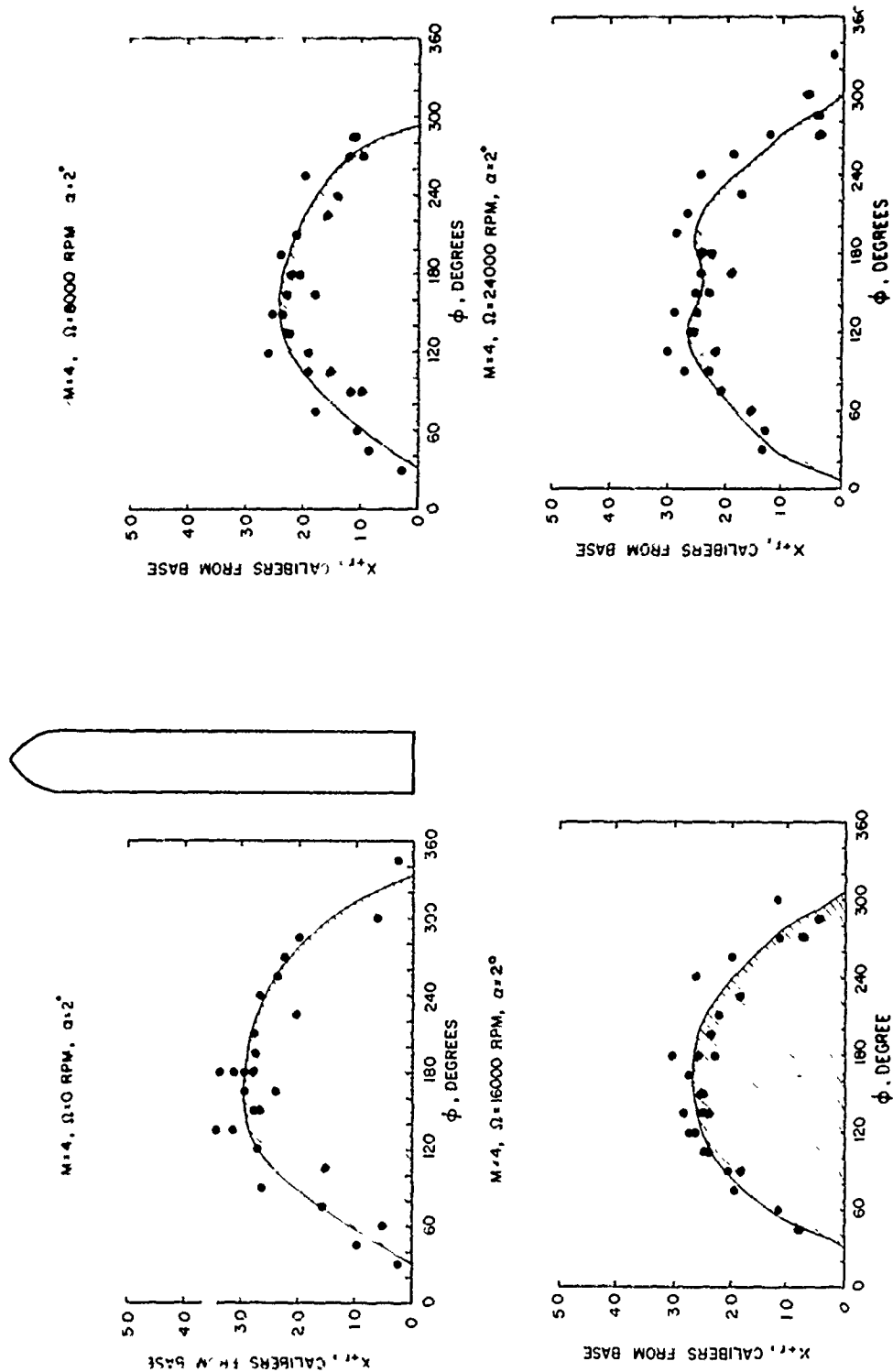


Figure 8. Boundary Layer Transition Data

a.  $M = 4$ ,  $\alpha = 2^\circ$

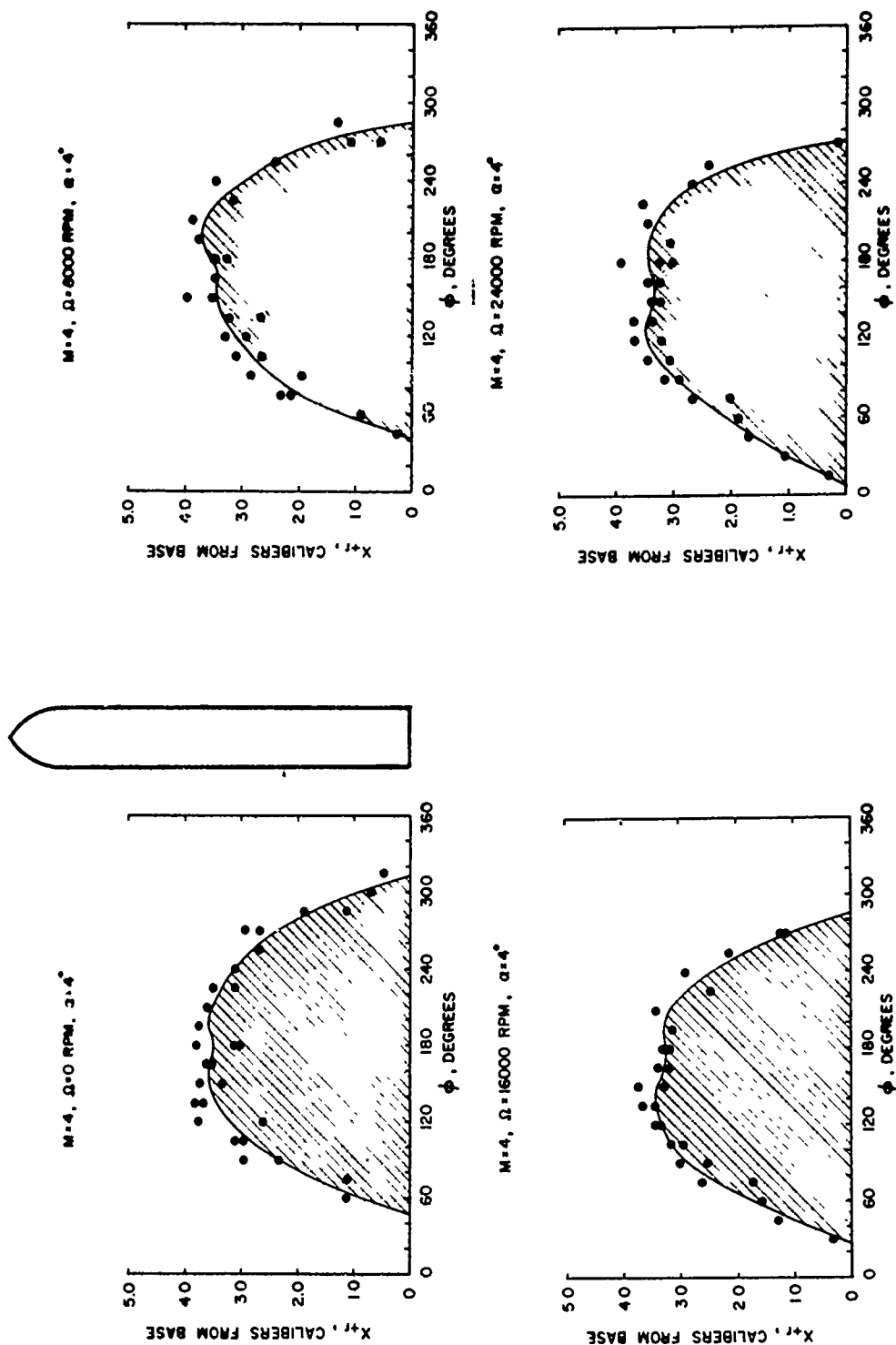


Figure 8. Concluded

b.  $M = 4, \alpha = 4^\circ$

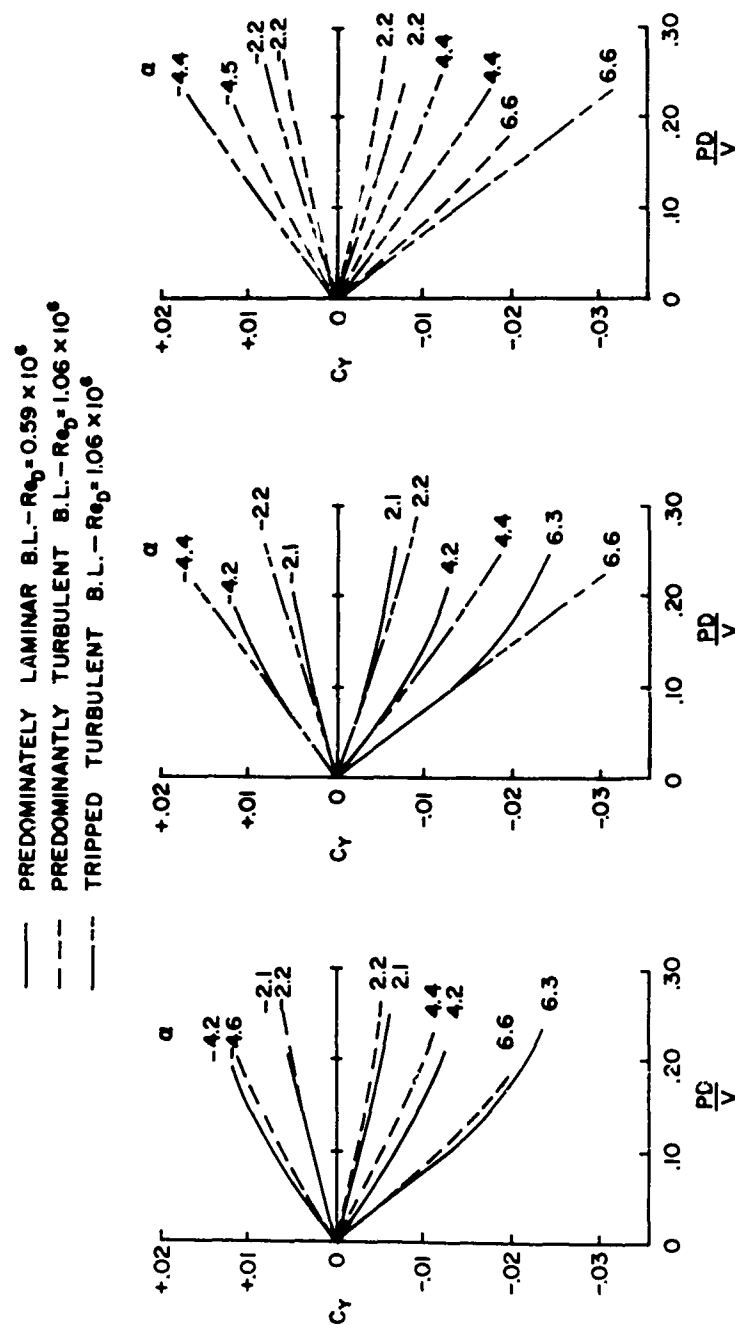


Figure 9. Comparison of Magnus Force Measurements for Different Boundary Layer Configurations,  $M = 3$

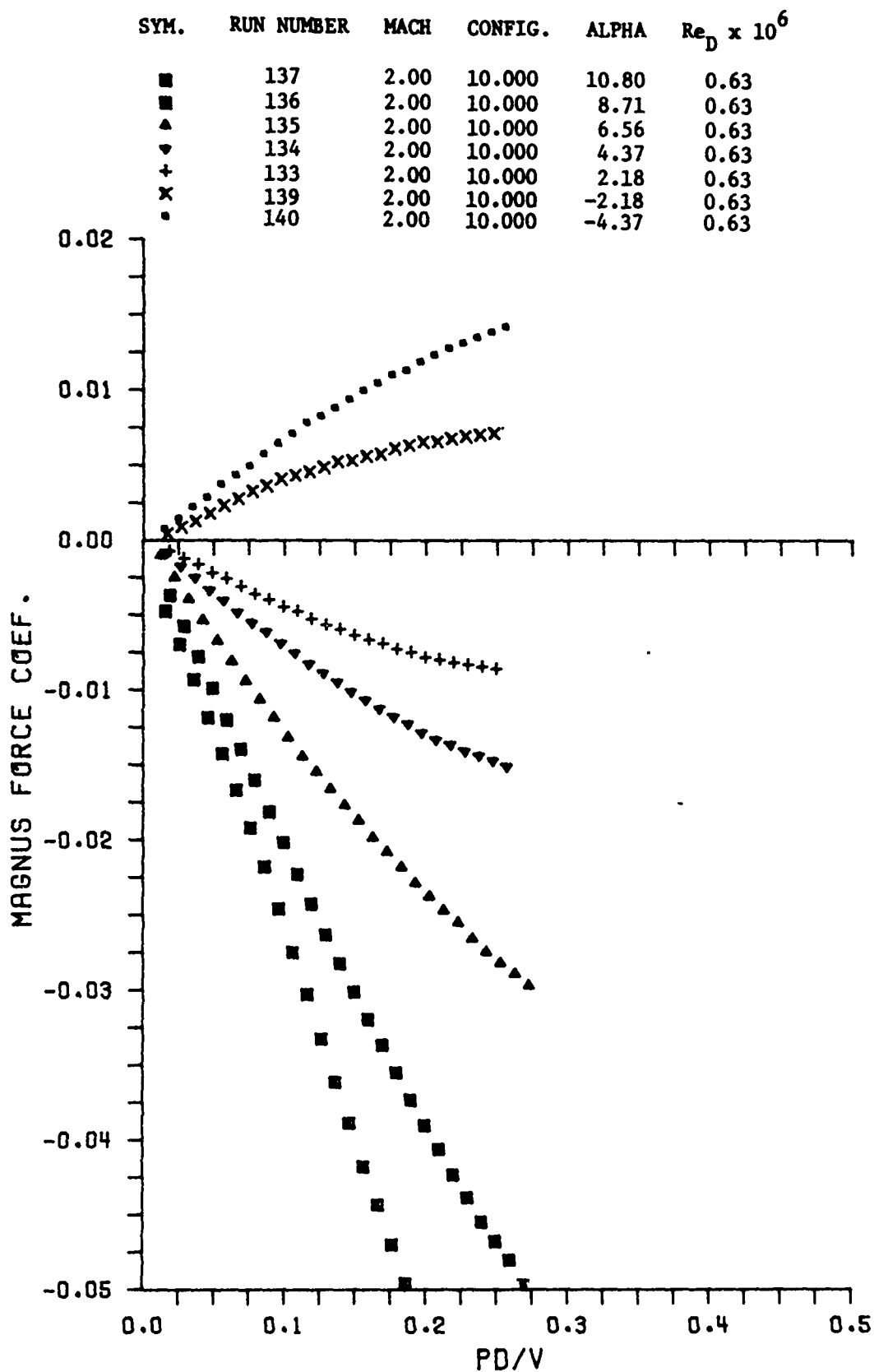


Figure 10a. Magnus Force Measurements for Low  $p_0$ , Natural Boundary Layer Transition--Predominantly Laminar Boundary Layer,  $M = 2$

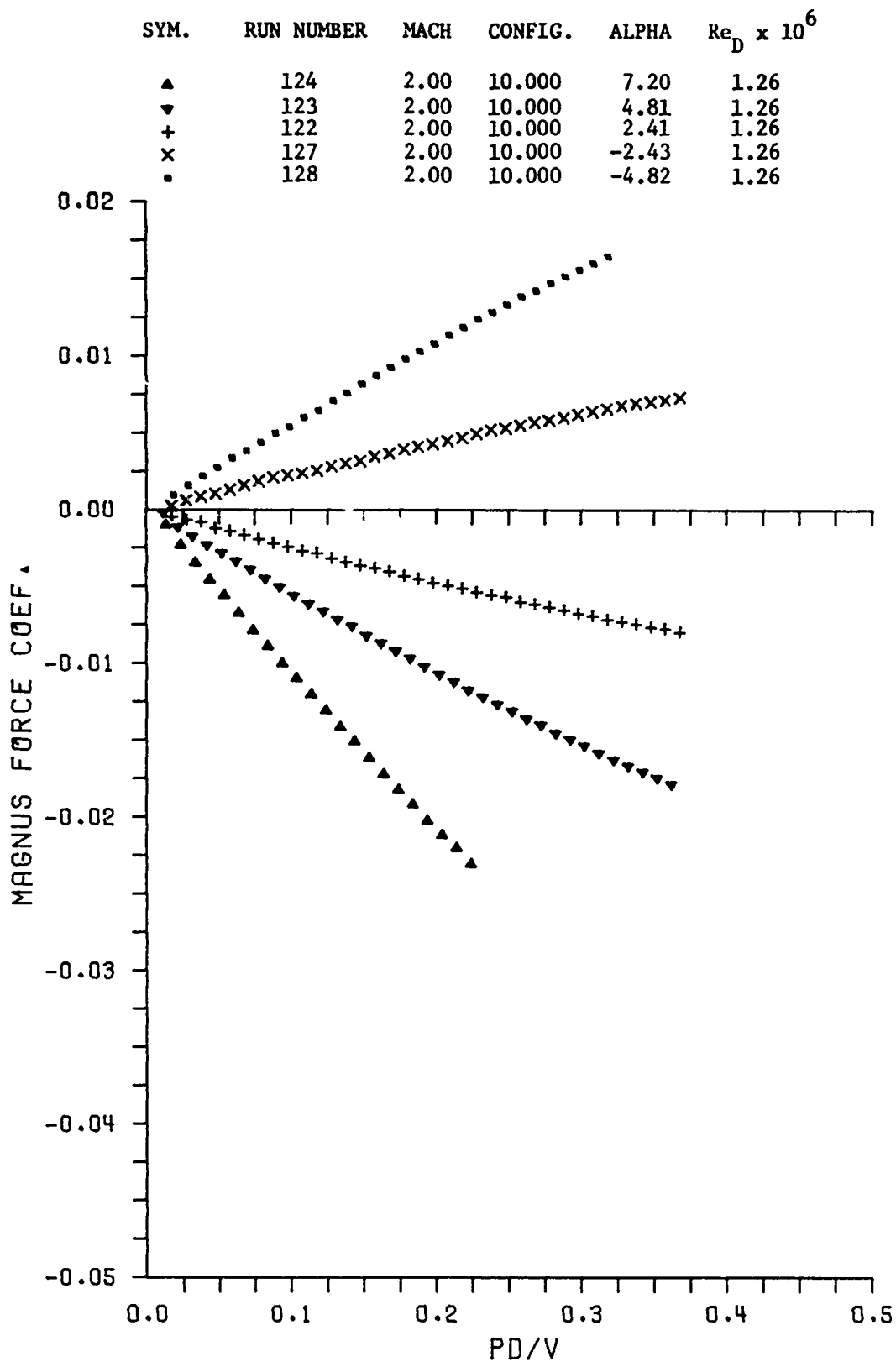


Figure 10b. Magnus Force Measurements for High  $p_0$ , Natural Boundary Layer Transition--Comparable Regions of Laminar and Turbulent Boundary Layer,  $M = 2$

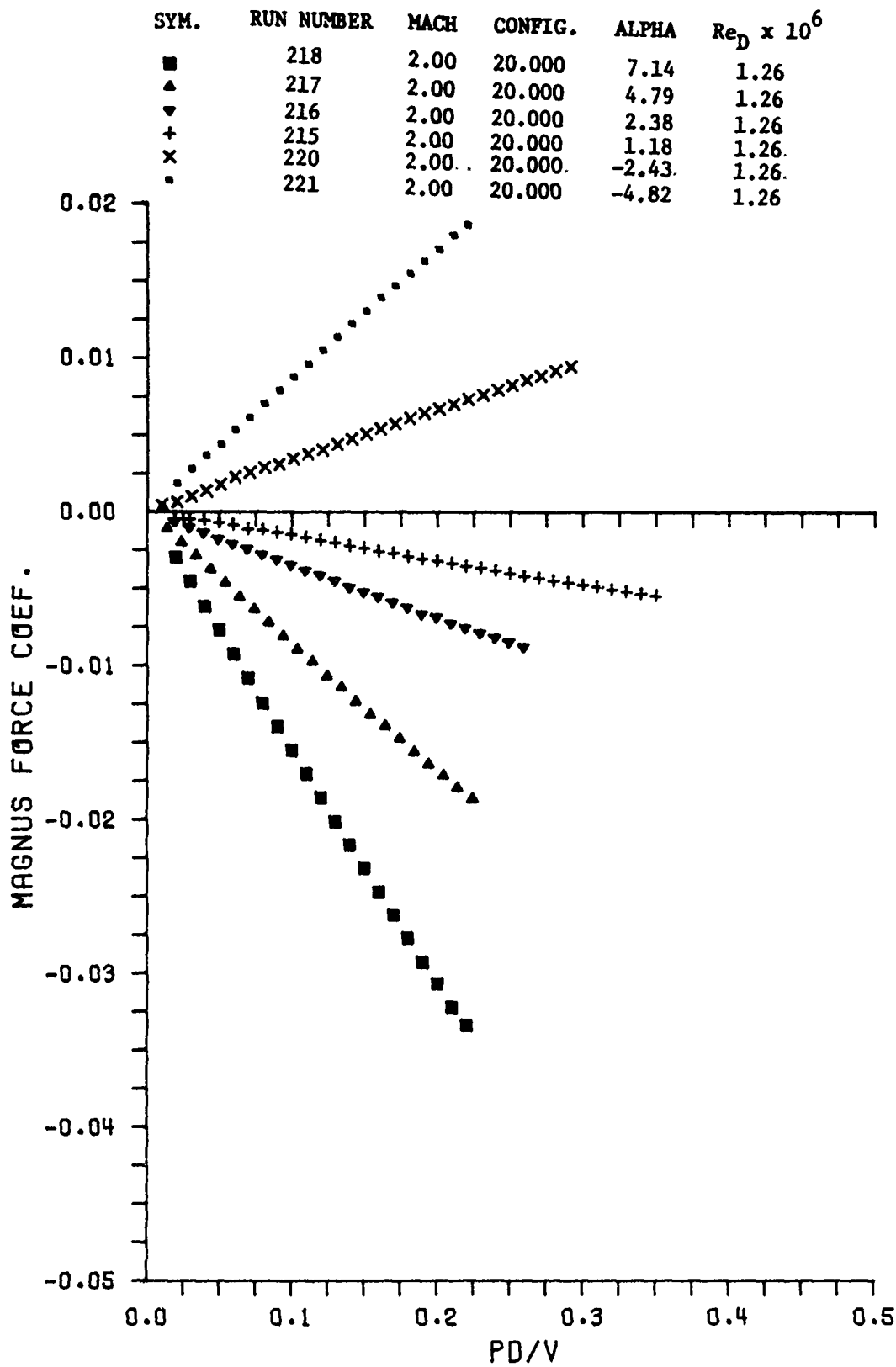


Figure 10c. Magnus Force Measurements for High  $p_o$ ,  
Tripped Turbulent Boundary Layer,  $M = 2$

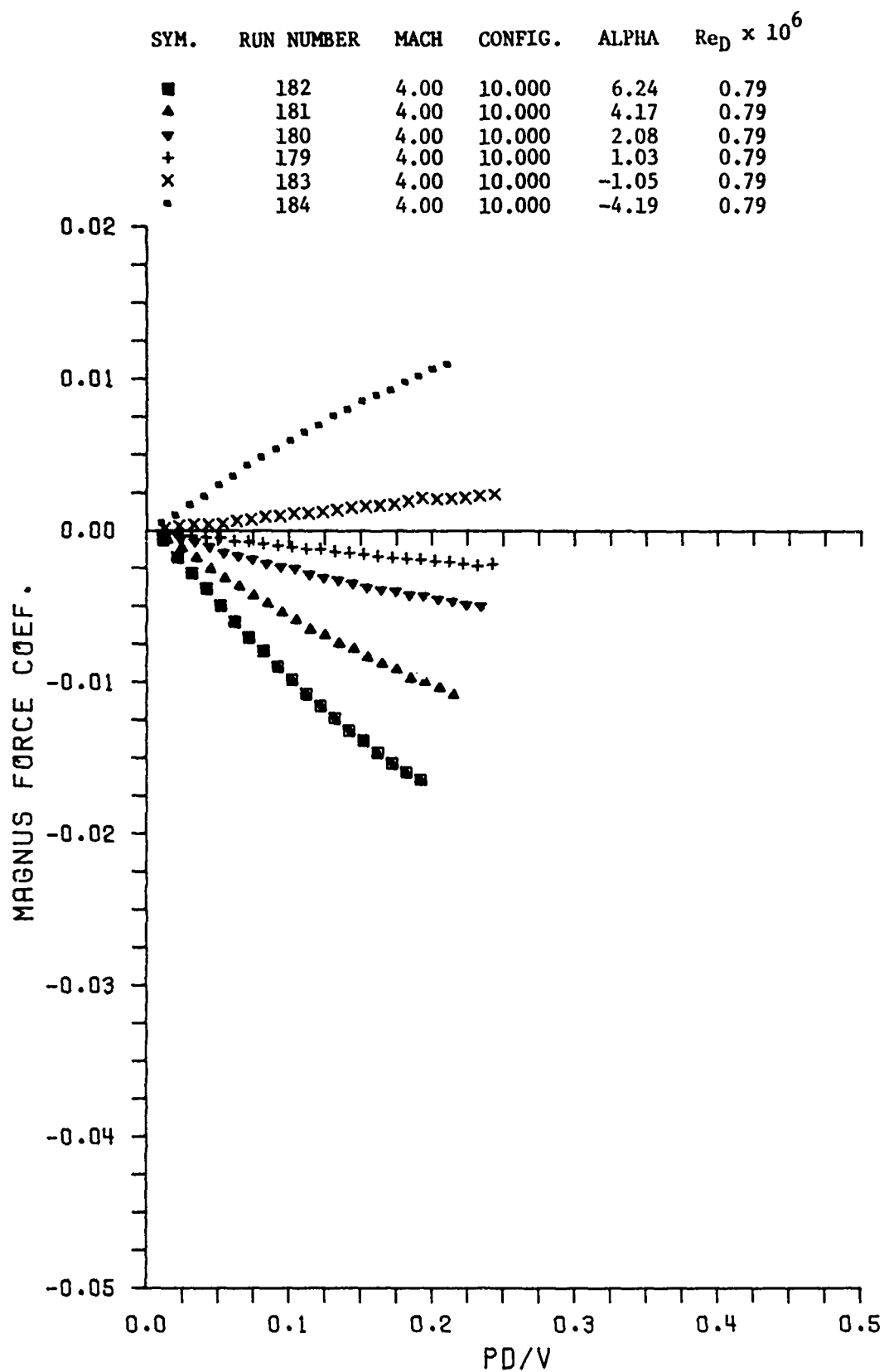


Figure 11a. Magnus Force Measurements for Low  $p_0$ , Natural Boundary Layer Transition--Predominantly Laminar Boundary Layer,  $M = 4$

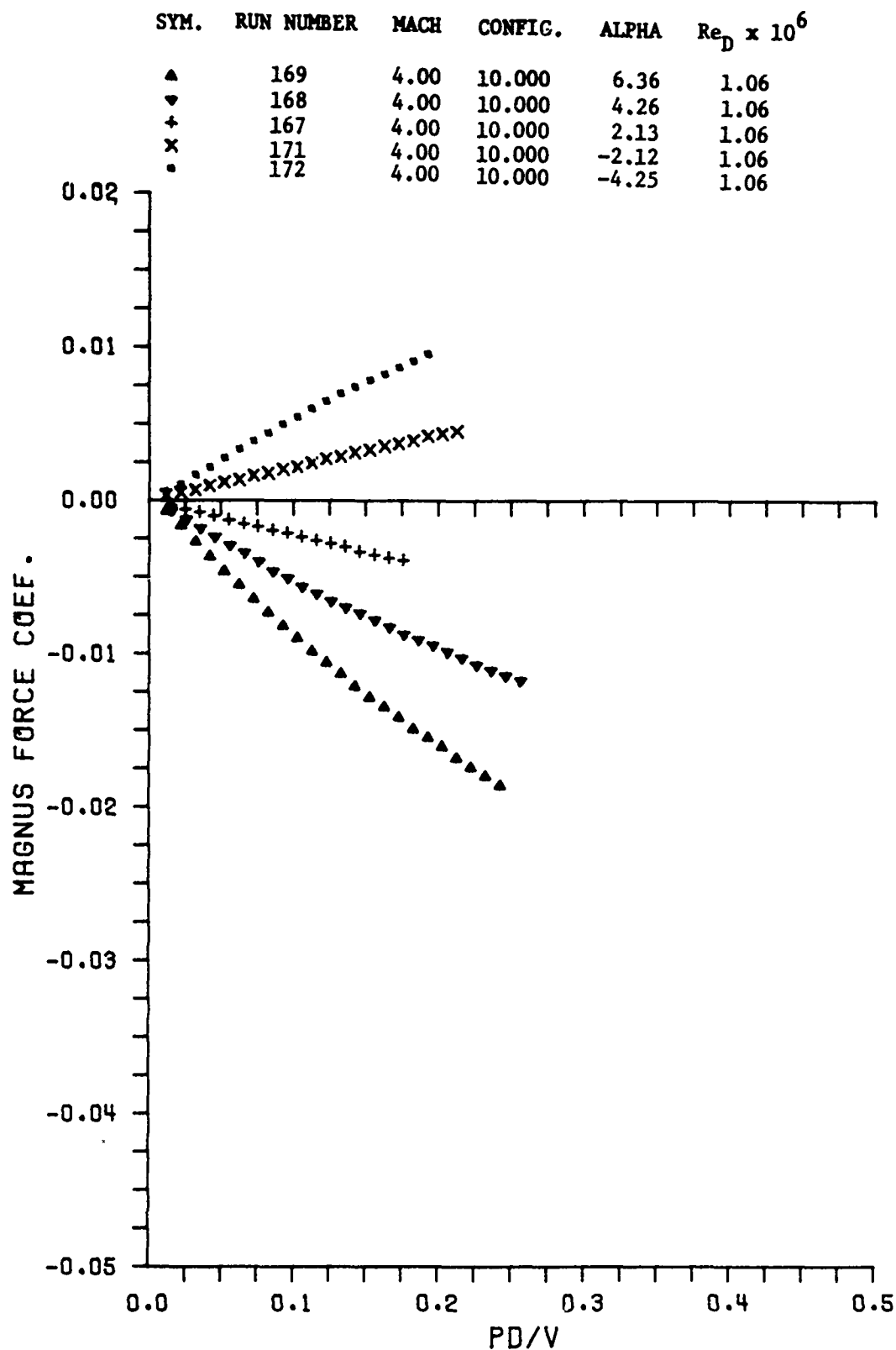


Figure 11b. Magnus Force Measurements for High  $p_0$ , Natural Boundary Layer Transition--Comparable Regions of Laminar and Turbulent Boundary Layer,  $M = 4$

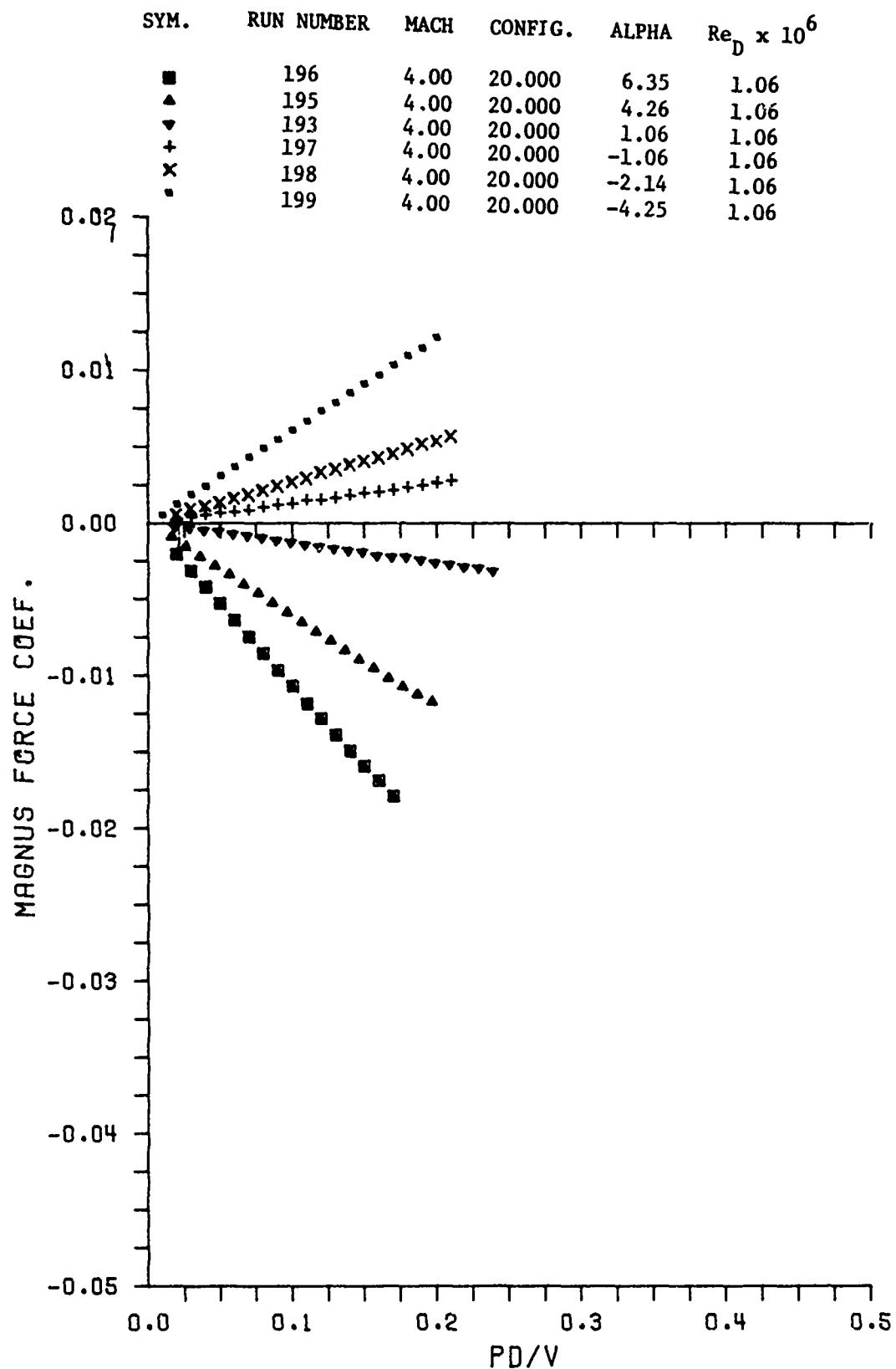


Figure 11c. Magnus Force Measurements for High  $p_o$ ,  
Tripped Turbulent Boundary Layer,  $M = 4$

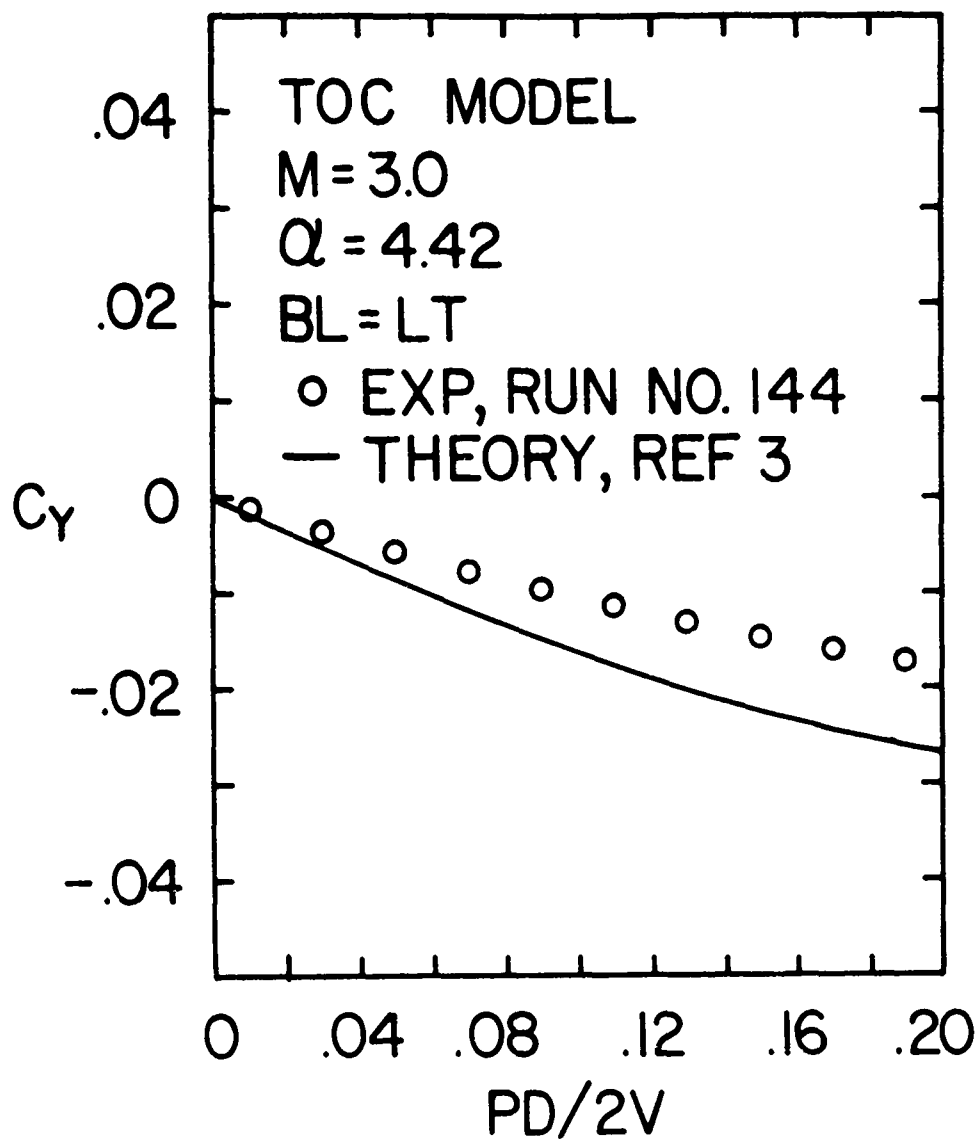


Figure 12. Comparison of Magnus Force Measurements to Theory, High  $p_0$

a. Natural Boundary Layer Transition,  $M = 3$ ,  $\alpha = 4.42^\circ$

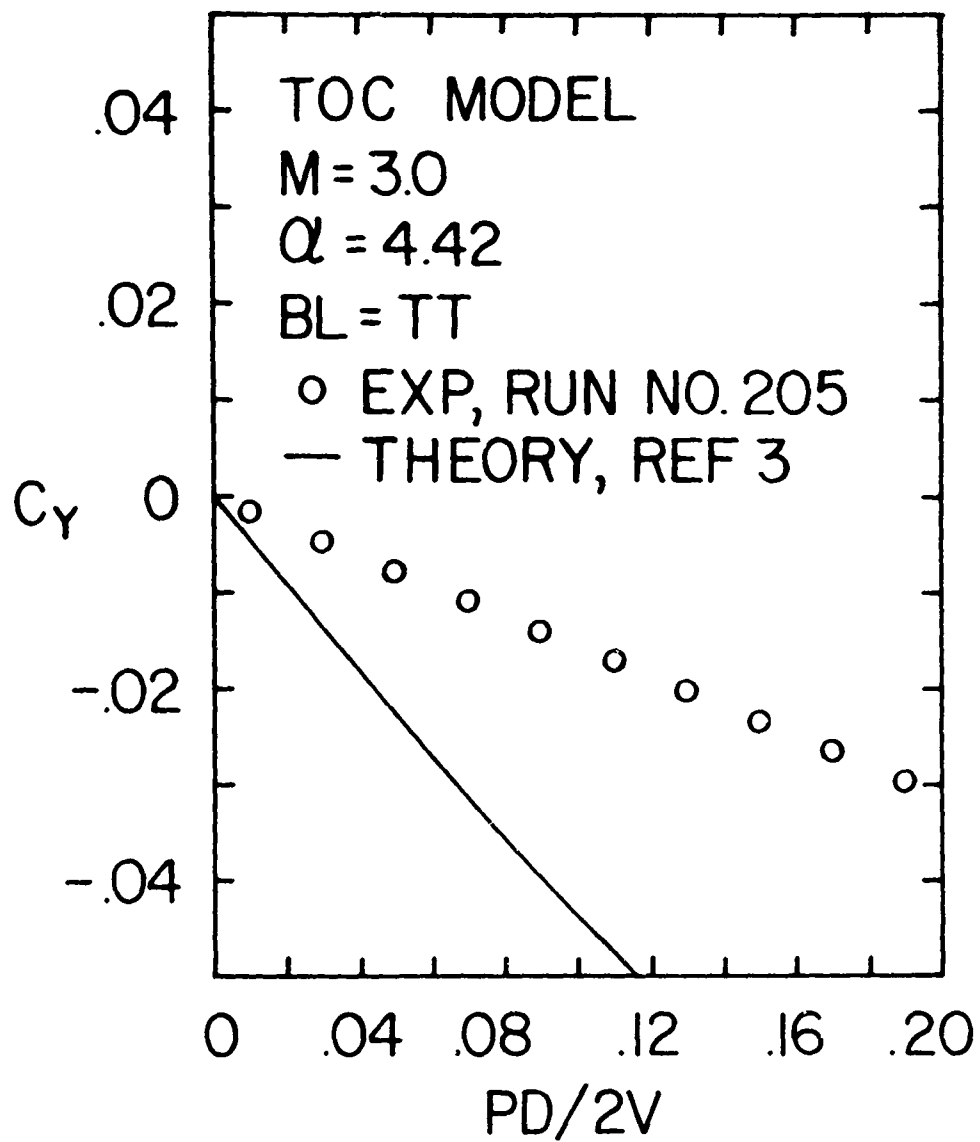


Figure 12. Concluded

b. Tripped Turbulent Boundary Layer,  $M = 3$ ,  $\alpha = 4.42^\circ$

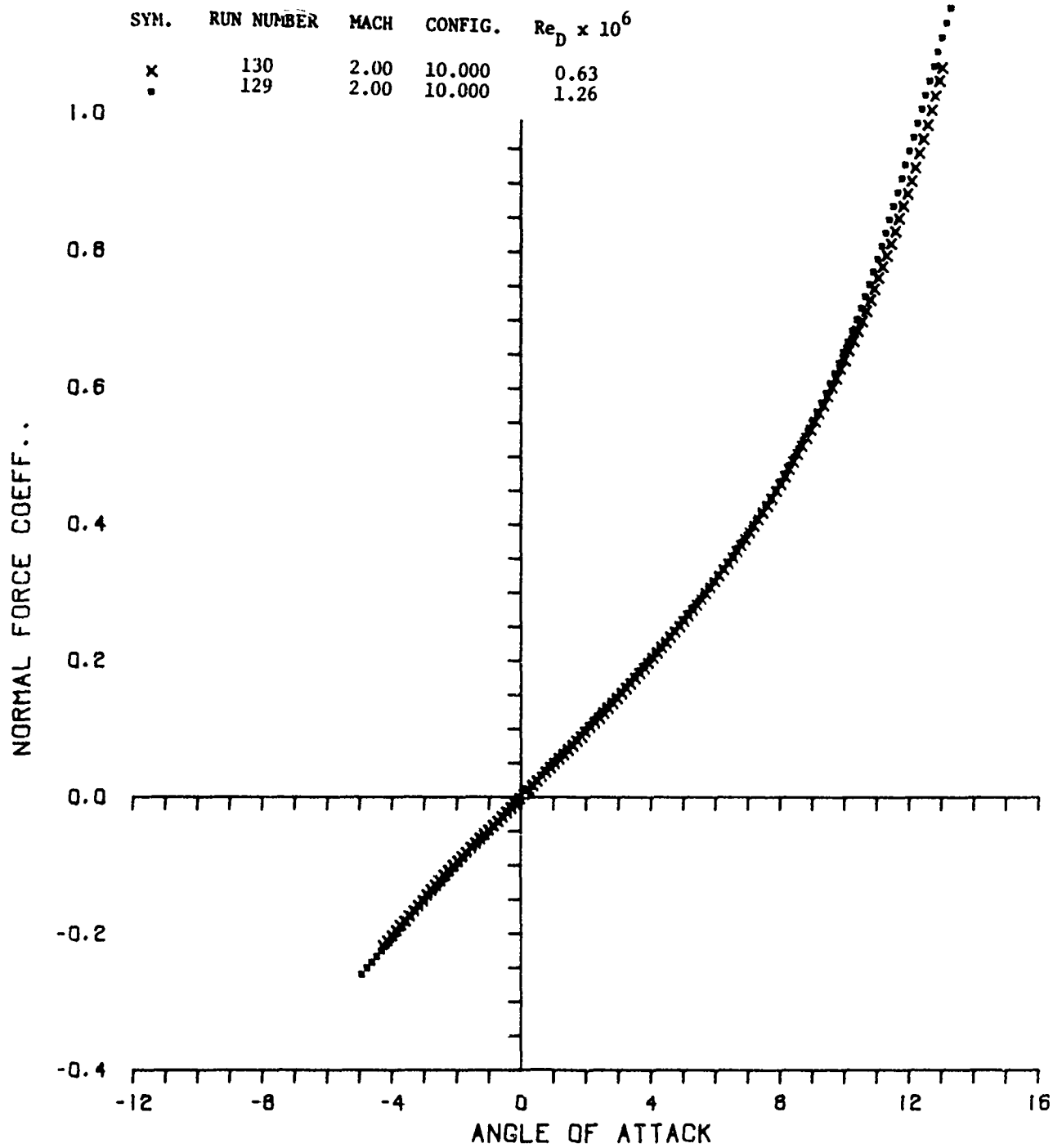
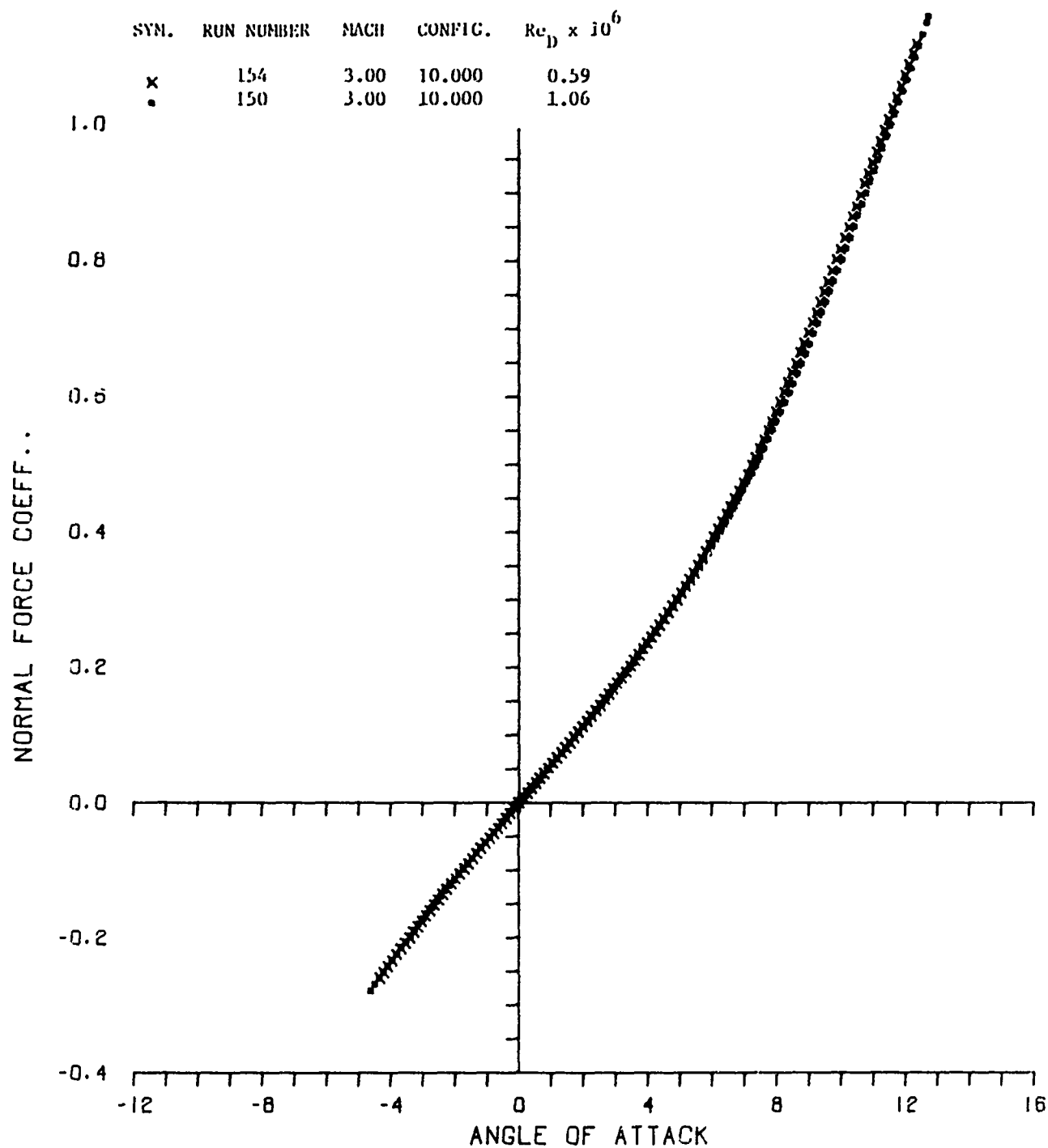


Figure 13. Normal Force Data

a.  $M = 2$



SYM.	RUN NUMBER	MACH	CONFIG.	$Re_D \times 10^6$
▼	200	4.00	20.000	1.06
+	185	4.00	10.000	0.79
x	173	4.00	10.000	0.79
•	164	4.00	10.000	1.06

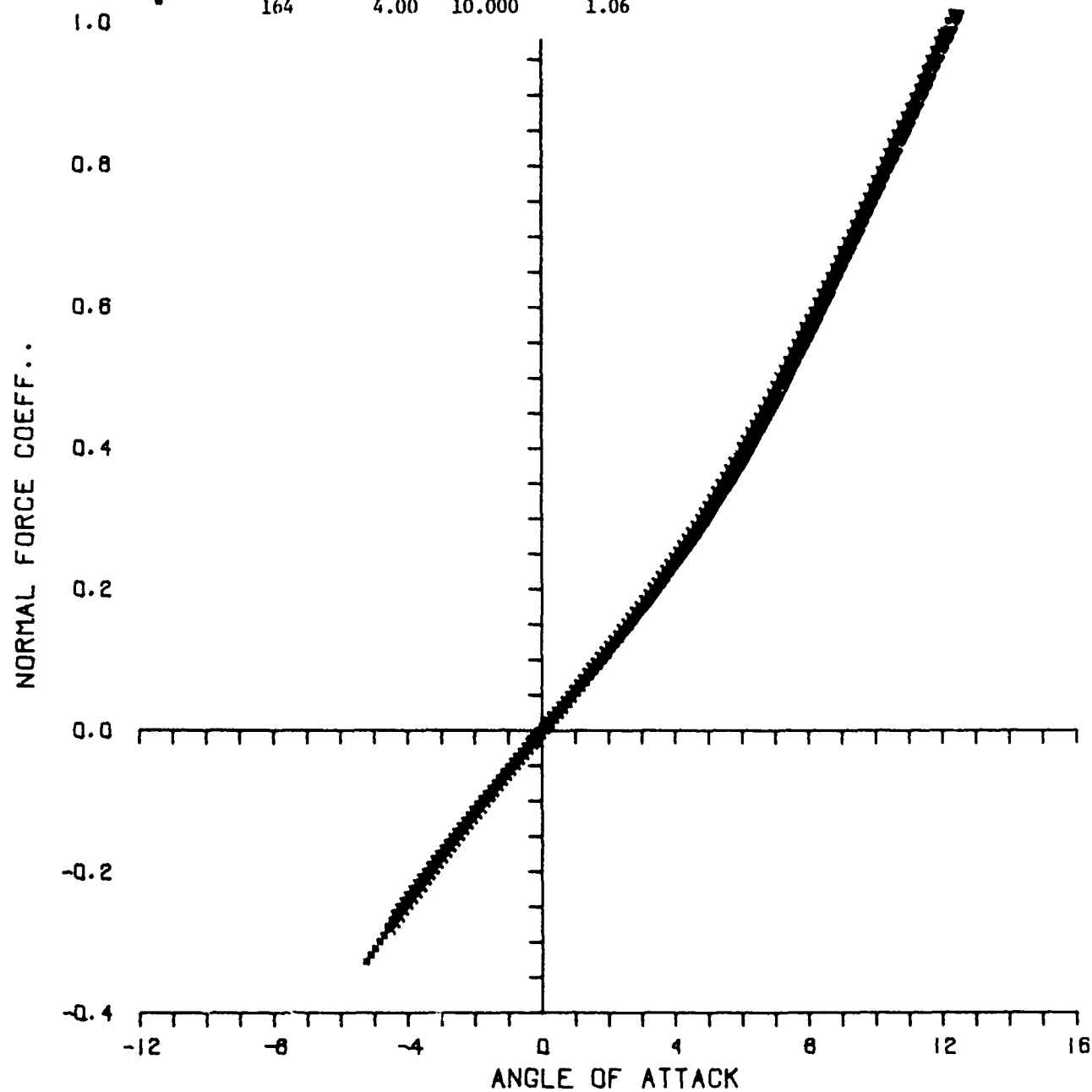


Figure 13. Concluded

c.  $M = 4$

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2. J. C. McMullen, "Wind Tunnel Testing Facilities at the Ballistic Research Laboratories," BRL Memorandum Report No. 1292, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, July 1960. AD 244180.
3. H. R. Vaughn and G. E. Reis, "A Magnus Theory for Bodies of Revolution," SC-RR-72 0537, Sandia Laboratories, Albuquerque, New Mexico, January 1973; also, *AIAA Journal*, Vol. 11, No. 10, p. 1396, October 1973.

# LIST OF SYMBOLS

ALPHA	angle of attack, degrees
BL = LT	natural transition, laminar and turbulent boundary layer
BL = TT	tripped turbulent boundary layer
$C_M$	pitching moment coefficient, $M_N/qSD\ell$ , referenced to model base
$C_N$	normal force coefficient, $F_N/qS$
$C_Y$	side (Magnus) force coefficient, $F_Y/qS$
$C_{YM}$	side (Magnus) moment coefficient, $M_Y/qSD\ell$ , referenced to model base
D	diameter of base of model, .0508 m
$F_N$	normal force
$F_Y$	side (Magnus) force
$\ell$	model length, 7 calibers = .3556 m
$M_N$	pitching moment, referenced to model base
$M_Y$	side (Magnus) moment, referenced to model base
$p_o$	tunnel total pressure, Pascals
P	spin rate of model, radians per second
PD/V	non-dimensional spin rate
q	free stream dynamic pressure, $\frac{1}{2} \rho V^2$
$Re_D$	Reynolds number based on model diameter and free stream properties
$Re_\ell$	Reynolds number based on model length and free stream properties
S	reference area, $\pi D^2/4$

# LIST OF SYMBOLS (Continued)

$T_o$	tunnel total temperature, degrees Kelvin
$V$	free stream velocity, cm per second
$X_{tr}$	location of boundary layer transition, calibers from model base
$\alpha$	angle of attack, degrees
$\rho$	free stream density
$\phi$	azimuthal position, equals zero on windward ray, see Figure 5
$\omega$	spin rate of model, revolutions per minute

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